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Disentangling the neural correlates of attention decrement: from Cognitive Neuroscience to Cognitive Engineering

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Declaration of authorship

I, Gérard Derosière, declare that this thesis titled "*Disentangling the neural correlates of attention decrement: from cognitive neuroscience to cognitive engineering*" is my own work and was done wholly while in candidature for a research degree at the co-supervising universities, namely the Montpellier-1 University (UM1) and the National University of Ireland Maynooth (NUIM).

I hereby assure that information derived from published work of others is always clearly attributed, the reference list being provided, and that the sources of quotations are always provided as well. Except from these quotations, this manuscript is entirely my own work. All sources of help have been explicitly acknowledged.

"Sans franchir la porte, on peut connaître le monde.
Sans regarder par la fenêtre, on peut voir le Ciel.
Plus on va loin, moins on apprend."

"Know the Universe without going out the door.
See the way of Heaven without peeping through the window.
The farther you go out, the far less you know."

Lao-Tzu (Tao-Tei-King, Chapter 47, VIth century B.C.)

À ma famille :

Mes parents, mes sœurs, et Marie.

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"*Il a foncé dans la rue, tout ce qui l'entourait le bottait, façon première manière, qui est devenue depuis bien plus triste et lucide aussi ; mais à l'époque, il dansait dans la rue comme un ludion, et moi je traînais la patte derrière lui, comme je l'ai toujours fait quand les gens m'intéressent, parce que les seuls qui m'intéressent sont les fous furieux, les furieux de la vie, les furieux du verbe, qui veulent tout à la fois, ceux qui ne baillent jamais, qui sont incapables de dire des banalités, mais qui flambent, qui flambent, qui flambent, jalonnant la nuit comme des cierges d'église.*"

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*C*ontents

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Abbreviations

AA: Adaptive Automation

ACC: Anterior Cingulate Cortex

ADHD: Attention Deficits Hyperactivity Disorders

APB: Abductor Pollicis Brevis

AVT: Auditory Vigilance Task

BCI: Brain-Computer Interface

BF: Basal Forebrain

BOLD: Blood-Oxygen Level Dependent

CBFv: Cerebral Blood Flow velocity

CBV: Cerebral Blood Volume

CMS: Common Mode Sense

CN: Caudate Nucleus

CPT: Continuous Performance Task/Test

CS: Cortico-Spinal

CW: Continuous Wave

DA: Dopamine

DPF: Differential Pathlength Factor

DRL: Driven Right Leg

EEG: Electroencephalography

EMG: Electromyography

ERD: Event-Related Desynchronization

ERP: Event-Related Potential

ESS: Epworth Sleepiness Scale

FA: False Alarm

FCR: Flexor Carpi Radialis

FDI: First Dorsal Interosseous

FFA: Fusiform Face Area

fMRI: functional Magnetic Resonance Imaging

FN: False Negatives

FP: False Positives

GABA: Gamma AminoButyric Acid

GP: Globus Pallidus

GPe: Globus Pallidus - external segment

GPi: Globus Pallidus - internal segment

HHb: deoxyhemoglobin

HRV: Heart Rate Variability

Hsup: Superimposed H-reflex

ICA: Independent Component Analysis

ICF: Intra-Cortical Facilitation

ICI: Intra-Cortical Inhibition

IOR: Inhibition Of Return

ISI: Inter-Stimuli Interval

IT: Inferior Temporal area

k-NN: k-Nearest Neighbors

LC: Locus Coeruleus

LDA: Linear Discriminant Analysis

LED: Light Emitting Diode

LICI: Long Intra-Cortical Inhibition

lM1: left primary motor area

LOOCV: Leave-One-Out Cross-Validation

LPFC: Lateral PreFrontal Cortex

lPFC: left PreFrontal Cortex

lPMC: left PreMotor Cortex

LRP: Lateralized Readiness Potential

M1: Primary motor area

MA: Mental Arithmetic

MCP: Multiple Comparison Problem

MEP: Motor-Evoked Potential

mPFC: medial PreFrontal Cortex

MT: Middle Temporal area

MVC: Maximal Voluntary Contraction

NA: Noradrenaline

NIRS: Near-InfraRed Spectroscopy

NMT: NeuroMuscular Tests

O_2Hb: Oxyhemoglobin

OCD: Obsessive-Compulsive Disorders

PET: Positron Emission Tomography

PFC: PreFrontal Cortex

PMC: PreMotor Cortex

PVT: Psychomotor Vigilance Task/Test

RBF: Radial Basis Function

rCBF: regional Cerebral Blood Flow

RF: Receptive Field

RN: Reticular Nucleus

ROC: Receiver Operator Charateristics

ROI: Region Of Interest

RP: Readiness Potential

RPE: Rate of Perceived Exertion

rPFC: right PreFrontal Cortex

rSO_2: regional Oxygen Saturation

RT: Reaction Time

SART: Sustained Attention to Response Task

SD: Standard Deviation

SICI: Short Intra-Cortical Inhibition

SMA: Supplementary Motor Area

SN: Substantia Nigra

SNc: Substantia Nigra pars compacta

SNr: Substantia Nigra pars reticulata

SSA: Stimulus-Specific Adaptation

SSVEP: Steady-State Visual Evoked Potential

STN: SubThalamic Nucleus

SVM: Support Vector Machine

TCDS: TransCranial Doppler Sonography

TC*i*: Thalamic relay Cell *i*

tDCS: transcranial Direct Current Stimulation

TEO: Temporo-Occipital area

TMS: Transcranial Magnetic Stimulation

TN: True Negatives

TOT: Time-On-Task

TP: True Positives

TRN*i*: Thalamic Reticular Nuclei cell *i*

TSD: Total Sleep Deprivation

TUT: Task-Unrelated-Thought

V1: Visual cortical area 1

V2: Visual cortical area 2

V3: Visual cortical area 3

V4: Visual cortical area 4

VEP: Visual-Evoked Potential

VL: Ventral Lateral (thalamic nuclei)

WN: White Noise

[HHb]: Deoxyhemoglobin concentration

[O2Hb]: Oxyhemoglobin concentration

[tHb]: Total hemoglobin concentration

5CSRT: 5 Choice Serial Reaction time Task

*I*ntroduction

"*Because it often happens that the understanding has only confused and imperfect perceptions of things, it is truly a cause of our errors [...]. It is therefore necessary to look for means to keep our perceptions from being confused and imperfect.*"

Nicolas Malebranche (1674)

What governs complex movements? What governs even the simplest ones, such as when we prepare to push the accelerator pedals in our cars while we wait at the red light? How do we succeed in listening to a conversation in the middle of a noisy party? What makes human beings listen rather than hear, and see rather than watch? At first glance, not a single process could master all these unrelated sensory-motor behaviors. Yet, focused attention does. Because of its astounding ubiquitous presence in human beings' activities, focused attention has since long fascinated philosophers (*e.g.*, Leibniz, 1765), psychologists (*e.g.*, James, 1890), neuroscientists (*e.g.*, Posner, 1980) and engineers (*e.g.*, Sheridan, 1974), among so many others. Still, the inability of humans to maintain states of focused attention over time – characterizing what is commonly referred to as attention decrement - remains a largely misunderstood phenomenon (Langner and Eickhoff, 2012), worthy of further investigation.

It is worth taking a moment to consider some of the negative effects associated with attention decrement especially in terms of its impact on our actions and perceptions. Over time-on-task (TOT), a novice violin player would undergo performance degradation in both the way he coordinates his fingers' movements and the way he distinguishes the different sounds produced by his instrument. Taken in more critical contexts, the consequences of such attention-related deteriorations of sensory-motor abilities may even be catastrophic. For instance, let us consider a neurosurgeon who must firmly focus his visual attention on your brain structures through your opened skull while performing a surgical task necessitating very fine manual dexterity. Let us further imagine that this procedure takes place over many hours – not uncommon in brain surgery. It is clear that degradation in attention and subsequent task performance could have serious repercussions under such a scenario! In the lab, behavioral markers of attention decrement manifest as increases in motor impulsivity (Manly et al., 1999; Robertson et al., 1997) and decreases in perceptual sensitivity (Helton and Russel, 2011), associated with longer response times to imperative signals (Lim et al., 2010). It is not a pleasant thought to contemplate that such sensory-motor deficiencies could occur in the behavior of any neurosurgeon performing life-critical surgery. Yet, people have only a finite attentional stamina, therefore this scenario is a more faithful representation of reality than the alternative assumption of unstinting task performance. Investigating the neural correlates of attention decrement is key to both *(i)* a deeper understanding of this common type of behavioral degradation in humans and *(ii)* the development of methods which can either compensate for its occurrence or warn of its presence.

1. Objectives and Approaches

What, *how* and *why* represent the three identified hierarchical levels of investigation in Science (Prediger et al., 2008). Cognitive Neuroscience presents no exception to this model of inquiry. In the case of the investigation of attention decrement, the approach should involve identifying, based on a systematic review of literature, *what* could be the neural structures underlying the previously mentioned sensory and motor dysfunctions observed at the behavioral level with TOT. This necessitates determining *what* neural structures are implicated in the functioning of the sensory- and motor-related focused attention processes under conditions of normal function. Once these neural structures are identified, the second step should involve elucidating *how* these structures behave under conditions of attention decrement. Finally, to complete the picture, interpretation and theoretical discussion have to be raised as regards to *why* such neural structures behave in the way they do. Adopting such an approach should lead to a better understanding of the familiar, daily-occurring, sensory-motor dysfunctions associated with the attention decrement phenomenon. The present thesis aims at doing precisely this.

Science aspires to understand nature for its own sake (Poincaré, 1905). Engineering, meanwhile, aims at "*producing complicated artifacts in an efficient way*" (Wang and Patel, 2000), with the intention of responding to humans' practical needs. Cognitive Engineering is no different. When one considers the hazards associated with attention decrement even during everyday activities it is no wonder that cognitive engineers have increasingly endeavored to develop cognitive state tracking systems, capable of detecting periods of attention disengagement based on physical (*e.g.*, blink duration, Caffier et al., 2003) and physiological markers (*e.g.*, skin conductance changes, Bundele and Banerjee, 2009). The recent emergence of passive brain-computer interfaces (BCI) is a good example of this approach (Parasuraman, 2012). Characterization of appropriate neural markers of attention decrement may represent a stepping stone to the development of practical passive BCI and, in turn, may lead to improvements in human safety. Such systems hold the promise of reducing accidents and human error-driven incidents that lead to loss of life and injury. The present thesis aims at doing so.

Thus, the objective of this thesis is twofold. First of all, through taking a Cognitive Neuroscience approach, this thesis seeks to shed further light on the neural underpinnings of the sensory-motor deficiencies associated with attention decrement. This will be achieved by first defining *what* brain structures are involved in the process according to the literature, and then investigating *how* and *why* they are involved in the processes which give rise to attention decrement. Secondly, by taking a Cognitive Engineering approach, this thesis will describe innovative means to track changes in attentional state in humans. To do so, this research focuses on an emerging optical neuroimaging technique - Near-InfraRed Spectroscopy (NIRS) - and aims to test the reliability of a number of neural markers of attention decrement as measured with this modality.

2. Contributions of the Thesis

2.1. Qualitative description

During the process of tackling the main objectives stated earlier, the work reported upon in this thesis has produced a number of contributions many of which have been published in appropriate form for wider dissemination purposes. These are detailed below.

1. A comprehensive literature review of the state of the art is provided regarding the functioning of focused attention. A primary contribution of this literature review is the establishment of a direct comparison of the neural correlates of sensory attention and motor attention, a comparison that has not been distinctly identified and discussed to date. This literature review posits a view that while focused attention is expressed in exactly the same way in sensory and motor cortices respectively, there are different neural networks supporting the two processes.

2. A comprehensive literature review of the state of the art is provided regarding the dysfunction of focused attention in conditions of attention decrement. I then identify *what* are the main neural structures worthy of further investigation to better understand this phenomenon.

3. Based on the results of two main investigations, a novel depiction is provided as regards to *how* attention decrement affects both the sensory and the motor cortices. I provide evidence that while focused attention manifests in the same way in the sensory cortices as in the motor cortices, attention decrement actually manifests in opposing ways in these structures. This unexpected finding is discussed with regards to the previously mentioned behavioral signatures of attention decrement, and actually provides a compelling explanation of these phenomena. I finally propose a potential explanation of *why* such changes in brain

activity - and then, in behavioral performance - occur during tasks requiring sustained attention. To do so, I refer to human evolution and to the existing interactions between sensory and motor attention.

4. A brief literature review is provided regarding the different physical and physiological markers that have been identified as relevant to the detection of attention decrements in humans. Among these existing markers, NIRS-measured cortical hemodynamic activity is further inspected. I then pinpoint the strengths and weaknesses of the NIRS technique in a specific field of cognitive engineering, that is, neuroergonomics. This subsection of the thesis provides a clear picture of the potential for using the NIRS technique within passive BCI, a use case which is growing rapidly.

5. Based on a machine learning data-driven investigation, I describe which NIRS-measured cortical hemodynamic variables are most relevant for exploitation within a passive BCI context. Last but not least, this thesis investigates which attention-related cortical area offers the best performance for the discrimination of states of attention decrement from states of full attention capacities. The results here provide novel and exciting findings, demonstrating that signals from the right parietal area provide better classification accuracies than signals from the prefrontal cortex (PFC). These results challenge current approaches to NIRS investigation in neuroergonomics which consist in exclusively focusing on changes in PFC activity.

2.2. List of publications arising from this work

The publications arising from this thesis covered two separate but related fields of investigation as follows:

From Cognitive Neuroscience...

1. Mandrick K, **Derosiere G**, Dray G, Coulon D, Micallef JP, Perrey S. (2013). Prefrontal cortex activity during motor tasks with additional mental load requiring attentional demand: a near-infrared spectroscopy study. *Neuroscience Research,* 76, 156-162.

2. **Derosiere G**, Billot M, Ward T, Perrey S. (2014). Adaptations of the motor neural structures' activity to lapses in attention. *Cerebral Cortex, doi: 10.1093/cercor/bht206.*

3. **Derosiere G**, Farrugia N, Perrey S, Ward T, Torre K. (In Press). Expectations induced by natural-like temporal fluctuations are independent of attention decrement: Evidence from behavior and early visual evoked potentials. *NeuroImage, doi: 10.1016/j.neuroimage.2014.09.015.*

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...to Cognitive Engineering

4. **Derosiere G,** Mandrick K, Dray G, Ward TE, Perrey S. (2013). NIRS-measured prefrontal cortex activity in neuroergonomics: strengths and weaknesses. *Front. Hum. Neurosci.* 7:583. doi: 10.3389/fnhum.2013.00583.

5. **Derosiere G**, Dalhoumi S, Perrey S, Ward T, Dray G. (2014). Towards a Near Infrared Spectroscopy based estimation of operator attentional state. *Plos One*. 9(3): e92045. doi:10.1371/journal.pone.0092045

6. **Derosiere G**, Dalhoumi S, Billot M, Perrey S, Ward ET, Dray G. (2013). Classification of NIRS-measured hemodynamics of the cerebral cortex to detect lapses in attention. *Proceedings of the 16th International Conference on Near-InfraRed Spectroscopy.*

Articles number 2, 4 and 5 are presented in their entirety in Chapters III, VI and VII, respectively. Further description of publications number 1, 3 and 6 is provided in Appendix A.

3. Outline of the manuscript

This thesis is divided in three parts and composed of eight chapters, the content of which is detailed in the following section.

PART I - COGNITIVE NEUROSCIENCE

Chapter I is titled "*On the definition, function and dysfunction of attention*". In the first half of this chapter, I address the issue of defining attention, with emphasis on the concept of focused attention. To do so, I adopt a chronological historical framework - extending from the very early conceptual analyses of attention in philosophy and cognitive psychology, to the very latest discoveries in neuroscience. The second section of this chapter is dedicated to the attention decrement phenomenon. I review and critique the relatively small number of studies which have investigated the neural correlates of the phenomenon and describe in some detail the main theories which have been proposed to explain the observed characteristics.

Chapter II is titled "*Visual attention decrement*". As previously mentioned, some of the results presented in this chapter have been subjected to an article currently submitted. These specific results relate to electroencephalography (EEG)-measured visual evoked potentials (VEP) results and provide evidence for a decrease in the visual neural response in conditions of attention decrement when compared to full attention capacity conditions. Further analyses have been realized (unpublished results) and are presented in the chapter. The results demonstrate an increase in the pre-stimulus alpha activity in visual cortices with TOT, the level of alpha activity having been identified as a marker of the level of cortical inhibition. Thus, taken together, these results provide evidence that attention decrement manifests as a decline in activity in the visual cortex.

Chapter III is titled "*Adaptations of motor neural structures' activity to lapses in attention*". This entire chapter has been published as a peer-reviewed article. The study is split into two experiments which explore attention decrement-related activity changes through *(i)* transcranial magnetic stimulation (TMS)-measured corticospinal (CS) excitability and *(ii)* NIRS-measured M1, premotor cortex (PMC), PFC and right parietal areas activities. Beyond corroborating established finding such as an increase in lateral PFC (LPFC) and right parietal areas activities, this study demonstrates that attention decrement manifests as a significant increase in CS excitability and in M1 activity.

Chapter IV is titled "*Neural signatures of attention decrement: motor over-excitability, sensory inhibition - Intermediate reflection*". In this chapter, a brief discussion about the results of chapters II and III - further discussed in chapter VIII - is provided. This chapter marks the point where the transition from Cognitive Neuroscience to Cognitive Engineering begins. Beyond the manifestation of attention decrement in the motor and sensory cortices, Chapter III demonstrates that NIRS-measured changes in relevant attention-related areas can be observed as well. These areas are comprised of the PFC and the right parietal area both of which are known to be involved in a large amount of attention-related activities. Thus, in the following chapters, a focus is made on the possibility of exploiting such activity changes in the PFC and right parietal areas to detect attention decrement.

PART II - COGNITIVE ENGINEERING

Chapter V is titled "*Cognitive Engineering implications of attention decrement neuroscience*". In this chapter, a brief literature review of the state-of-the-art is provided regarding known physical and physiological markers of attention decrement in cognitive engineering. The chapter ends with a focus on the recent emergence of passive BCI and specifically how this might be achieved through the technique of NIRS.

Chapter VI is titled "*NIRS-measured prefrontal cortex activity in neuroergonomics: strengths and weaknesses*". Again, the entire chapter has been published in the form of a peer-reviewed article (as mentioned on p. 26). As its title suggests, the chapter is comprised of a short review, which enumerates a number of advantages to using the NIRS technique in the context of neuroergonomics - mostly with the intention of developing passive BCI. Specifically, a focus is made on the PFC, as this cortical area has thus far been the major source of investigation for NIRS-based neuroergonomics studies. Some weaknesses are also identified, which in turn lead to some observations regarding the need for investigation to ascertain the possible utility of a range of different NIRS-derived cortical hemodynamic variables.

Chapter VII is titled "*Towards a Near Infrared Spectroscopy-based estimation of operator attentional state*". As previously mentioned, the entire chapter constitutes a peer-reviewed publication (please see p. 26). In this study, a part of the NIRS data recorded in the study from Chapter II was further analyzed by a machine learning data-driven approach to address two main issues. The first pertains to defining which NIRS-measured hemodynamic variable(s) would afford the best classification accuracy results for the detection of attention decrements. The second aim of the study is to test whether NIRS signals from the right parietal area may - in addition to the NIRS signals from the PFC - facilitate the detection of attention decrement with high classification performance. The findings demonstrate that the NIRS variables are not equal in terms of classification accuracy for detecting attention decrements. The results suggest that the oxy-hemoglobin (O_2Hb) variable offers the best results. Further, a substantial result from the data-driven approach is that the right parietal area allows for better classification accuracy results than the PFC.

PART III - EPILOGUE

Finally, Chapter VIII is titled "*Towards a disentangling of the neural correlates of attention decrement*". This chapter couples discussion regarding both the Cognitive Neuroscience and the Cognitive Engineering approaches taken in the present thesis. The conclusion is provided by summing up the main contributions of the thesis and proposing novel avenues of research arising from this work.

- PART I -

COGNITIVE NEUROSCIENCE

Chapter I

On the definition, function and dysfunction of attention

"*Attention please! Attention please!*
Don't dare to talk! Don't dare to sneeze!
Don't doze or daydream! Stay awake!
Your health, your very life's at stake!
Ho–ho, you say, they can't mean me.
Ha–ha, we answer, wait and see."

Roald Dahl (1972)

1. What is "Attention"?

"*Attention please, train DB105 is arriving on platform A*", said the voice over the loudspeaker. I was at Pearse Station, Dublin, and as soon as I heard the first two words of the train announcement I intuitively focused on that source of auditory information and prepared to react. And everyone there probably behaved in the same way. Similarly, readers of the Roald Dahl poem quoted on this chapter's front page, when they glanced at the first line: "*Attention please! Attention please!*", will surely have further focused on that piece of poetry. Try reading the poem again, the sensation of focus is powerful. William James (1890) referred to this universal intuition regarding attention when he said "*Everyone knows what attention is*", a remark that all psychologists can quote by heart. Yet, at the dawn of the 21st century, scientists are still attempting to understand attention, in fields ranging from psychology, to cognitive neuroscience, computational neuroscience, ergonomics and more. "*No one knows what attention is*", Pashler (1998) stated provocatively. So, who is right, James or Pashler?

The very first step of any scientific investigation is, in my opinion, to define the scientific epistemological framework. This is especially the case with attention, as its definition and roles have been debated for decades, indeed, for centuries. In this section, my aim is to provide the reader with a definition of attention and a description of its functions. To do so, I have not only based my reviewing work on modern findings from psychology and neuroscience, but I have also returned to the philosophical origin of the conceptual work on attention which is all too often forgotten by contemporary neuroscientists.

1.1. Before cognitive psychology: from philosophy to behaviorism

The first discussions on the nature of attention were held by philosophers, from around the 17th to the mid 19th century. During this period, attention was studied in terms of metaphysical issues related to perception, thoughts, conscious awareness or, in other words, how we come to know the physical world. While studying this history, I noticed that many of the philosophers' initial ideas are still found in current cognitive theories of attention. Here I present a selection of these early empirical studies, with an emphasis on their contemporary influence on how attention is apprehended, defined, and investigated.

> "*While the sense organs are occupied with one object, they cannot simultaneously be moved by another so that an image of both arises. There cannot therefore be two images of two objects but one put together from the action of both.*", assumed Hobbes (1655).

Though he did not directly mention attention in this quote, Hobbes nevertheless pointed out two key ideas that are strongly connected to current definitions of attention. The first substantial idea is that humans' perceptual systems possess a *limited capacity* to cope with the sensory world. The second one - closely related to the first - is that humans' perception is a selective process, dealing with one object at a time. Similarly, Malebranche (1674) noted that human beings have to constantly organize their incoming perceptions of the physical world, while simultaneously restraining themselves from the distraction arising from emotion. According to him, attention represents the key faculty allowing for the prioritization of information. Malebranche was the first to evoke attention as allowing the suppression of distractive sources (*i.e.*, emotions in this case).

The next major contribution came from Leibniz (1765) who told us that the prioritization of information might be performed in two ways. He described that attention can be exogenously oriented by sensory stimulation present in the environment, or endogenously oriented, that is, following ones' intention. This observation makes us think about the distinction most used by contemporary psychologists and neuroscientists (*e.g.*, Sarter et al., 2001) to describe how attention can be captured: *i.e.*, through top-down[1] or bottom-up[2] processes. Leibniz was, somehow, at the origin of this distinction. Panum (1858) re-exploited the same conceptual separation between exogenous and endogenous orienting of attention and further described the exogenous process. He observed he was able to "*see*" only a certain number of objects simultaneously (*i.e.*, as opposed to Hobbes who considered that humans' perception was restricted to one object at a time) and that objects perceived at the very first glance were those characterized by strong salience. Also, Panum noticed that, while studying an object, attention was first directed to that object without any eye movement, and then came the movement of the eyes. These observations by Panum have had, in my opinion, significant

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[1] Also referred to as knowledge-driven, endogenous, volitional/intentional orienting of attention.

[2] Also referred to as stimulus-driven, exogenous, unintentional orienting of attention.

impact on the studies of attention. For instance, the so-called "*pop-out effect*" which is commonly investigated nowadays (*e.g.*, Hershler and Hochstein, 2005) and which represents the tendency of one's attention to be caught by attractive stimuli, clearly relates to the first remark of Panum (*i.e.*, that objects with strong salience are the first to be perceived). Further, his second remark (*i.e.*, that attention can be directed without any movement of the eyes) remind us that there is a distinction between overt and covert[3] attention, today inherently accepted by any experimentalist who exploit visuo-spatial tasks. Panum was arguably the first to highlight the relationship between attention and eye movement. Other links between attention and movement have been proposed by Bain (1888) who considered, that attention can be directed to actions in cases of non-automated limb movements. Again, the role of attention in movement preparation - namely motor attention (*e.g.*, Rushworth et al., 2001) - has since become a topic of interest in neuroscience (see subsection 1.2.5., p. 50), Bain being the first to have considered such a linkage. Finally, one last philosophical work on attention that I would cite is that of Hamilton (1859). Complementarily to Panum's observations on exogenous attention, Hamilton suggested that endogenously controlled attention is limited to the holding of a certain amount of objects in "*mind*" at a time. According to him:

> *"The doctrine that the mind can attend to [...] only a single object at a time would in fact involve the conclusion that all comparison and discrimination are impossible. [...] Suppose that the mind is not limited to the simultaneous consideration of a single object, a question arises: how many objects can it embrace at once?"*

This kind of question strongly influenced the way attention was studied in the ensuing years. In the mid 19th century, under the influence of positivism[4], psychology became an independent scientific discipline (*i.e.*, independent from philosophy) and the concept of attention was subjected to experimental investigation. Early experimentalists consequently shaped opinion on *how* best to address attention-related issues. An important step in terms of the development of psychophysical methods was initiated by Donders who exploited the

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[3] According to Klein and Lawrence (2012) "*overt attention manifests as eye movements that seek to place the visual information at the fovea where detail sensitivity is highest, and covert attention manifests as improvements in information processing of spatially localized stimuli in the absence of eye movements*".

[4] Positivism: "*A philosophical system recognizing only that which can be scientifically verified or which is capable of logical or mathematical proof, and therefore rejecting metaphysics.*" According to the Oxford Dictionary.

difference between simple reaction time (RT) and choice RT[5] to infer differences in "information processing". This was the beginning of "*mental chronometry*", today widely exploited in psychology and neuroscience to investigate attention - it is used in this thesis for example (*e.g.*, see Chapter II). Examples of findings from the early experiments on attention include the work of Jevons (1871) and Cattell (1885) who both experimentally addressed the question of "*How many objects can [attention] embrace at once?*" (*i.e.*, the previously mentioned issue which had provoked Hamilton's deliberations on attention) in the visuo-spatial domain. To do so, Cattell exploited the tachistoscope[6] - a notable innovation in itself. He discovered that endogenous attention, in addition to presenting a span in space, also had a span in time, with attention level actually fluctuating over time. The idea of a span of attention over time was mentioned by Breese (1899) as well, who proposed that the switch from one stimulus to another in the binocular rivalry phenomenon[7] was related to fluctuation in attention over time. These early ideas remain relevant even now, and are reflected in a large amount of contemporary research such as for instance in studies on temporal orienting of attention (*e.g.*, Lange, 2013) or TOT-related attention lapses (*e.g.*, Lim et al., 2010).

It was in the context of this effervescent interest in the experimental testing of attention that James wrote in 1890 one of the best-known quote in the field of psychology, which while already mentioned is worth reproducing again here: "*Everyone knows what attention is*". Following this period emerged the behaviorist approach, which focused on the relationships between observable behavior and sensory stimulations. The impact of the behaviorist perspective was very little in terms of an understanding of the process of attention, as this approach was not focused on explaining how mental processes are affected by sensory stimulations or related preparation of motor responses. Research on attention waned then until the 1950s[8], when the cognitive approach took precedence over behaviorism. Contrary to the behaviorist approach, the cognitive approach considered that mental processes which were not directly observable - such as attention - could represent objects of scientific investigation. This was a key milestone in the scientific pursuit of the understanding of attention processes

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[5] In simple RT tasks, there is only one response and only one stimulus possible. In choice RT, different stimuli are presented and distinct responses are required by the subjects for each possible class of stimuli. A third type of RT tasks is recognition RT tasks in which different stimuli are presented and subjects have to recognize and answer to only one of the stimuli.

[6] A tachistoscope is a tool which allows for presenting a group of stimuli in a very brief manner. This allows to finely control the presentation parameters in terms of time and intensity.

[7] In binocular rivalry, visual perception alternates between two images presented to each eye.

[8] Nonetheless, research on attention did not totally stop during this period. For a discussion relating to the few behaviorist contributions to the field of attention, please refer to the book "Neurobiology of Attention", p. XXIV. As I consider these works as not substantial for the rest of my dissertation I prefer not to mention them.

and in the following sections we will devote some time to describing the main theoretical contributions of the cognitive approach to the understanding of attention. In particular, most of the cognitive theories I will describe had more influence in understanding endogenous control in attention rather than exogenous elements. Also, as the object of my thesis concerns sustained - and in fact endogenously controlled - attention, I will focus the rest of my dissertation on precisely this aspect which I refer to as endogenous attention. Before focusing on that interesting period of research on attention, I suggest that the reader should refer to the "*Reminder Box*", below, which summarizes the take-home messages of the first subsection.

Reminder Box I

Perception has to be selective (Hobbes,1655).
Attention allows for prioritizing information (Malebranche, 1674).
Attention can be endogenously or exogenously oriented (Leibniz, 1765).
Exogenous attention is influenced by stimulus salience (Panum, 1858).
Attention can be directed without eyes movement (Panum, 1858).
Attention can be directed to movement as well (Bain, 1888).
Endogenous attention has a span in time and space (e.g., Cattell, 1885).

1.2. Cognitive theories of attention

The revival of interest in attention research arguably arose from the work of Mackworth in 1948 who sought an understanding of the decrements in attention over time observed in radar operators during the World War II. However, theoretical contributions in that domain of attention research (*i.e.*, attention decrement, TOT effect) remained scarce until the early 1990s and are further described in the second section of this chapter (*i.e.*, Section 2. On the inability of humans to sustain attention). The present subsection focused on theoretical advances made by leading cognitive psychologists on how endogenous attention operates in what I would call "*efficient conditions*", that is, in the absence of attention lapses[9].

1.2.1. On the selectivity of attention

While major philosophical contributions and early experiments on attention were mainly described in the visual domain (see above), the first theoretical advances made in cognitive psychology addressed the issue in the auditory domain. It is however worth noting that the questions raised by early cognitive psychologists were closely related to the previously mentioned philosophical discussion on attention, with a major focus on understanding the selection processes associated with attention. Cherry (1953) for instance introduced the "*cocktail party problem*"[10] and pioneered dichotic listening experiments to study this kind of problem. In his dichotic listening experiments, Cherry presented two streams of different words to the subjects simultaneously, distributing one stream by ear through a set of headphones. Subjects were required to focus their attention on one of the two streams of words and to repeat as rapidly as possible these attended words. After the task, participants were asked to also recall the words of the unattended stream. They were incapable of doing this and indeed participants did not even notice if the unattended words shifted to another - foreign - language. Even more compelling is work by Moray (1959) who found that if the unattended stream was composed of a repetition of the same word for the duration of the task, participants still could not identify it. Taken together, these findings suggest that unattended stimuli were filtered out. On this basis, Broadbent (1958) developed the first cognitive model of focused attention, known as the Broadbent's filter model[11]. Broadbent developed a theory which suggested that attention acts as a filter, present at an early stage in humans' information processing systems, which allows for selective information processing in the environment (see Figure 1.1.A.). According to this theory, attention performs this early selection based on certain simple criteria, mostly physical properties, such as the location (*e.g.*, as in Cherry's experiments, the attended ear representing the attended location/side) or the pitch of the stimulus. The extraction of the words' meaning, as well as all

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[9] The aim here is to first provide the reader with a view on how attention operates without dysfunction.

[10] The "*cocktail party problem*" describes our ability to focus our attention on a specific source of auditory information to converse with someone at a noisy cocktail party.

[11] It is worth remarking that this was the first popular information processing metaphor in the cognitive psychology literature, and illustrates the influence of computationalism (*i.e.*, theory that humans' brains function as Turing machine) over psychology during this period.

higher-level processing, takes place at a post-filtering stage. It is worth remarking that this filter model explains some well-known (in)attention-related phenomenon such as inattentional blindness and deafness. Inattentional blindness/deafness occurs when ones fail to perceive an unattended stimulus because the locus of attention is fully occupied by other relevant stimuli (*e.g.*, see the experiments of Simons, reviewed in part in Simons, 2000). In this case, blindness and deafness may be regarded as a consequence of the attentional "*all-or-nothing*" filter described by Broadbent.

Although Broadbent's filter model would appear convincing at first glance, it however runs into difficulties when used to explain certain experimental observations. For instance, Moray (1959) observed that participants stopped doing the task if they were presented with the instruction "*You may now stop*" in the unattended ear. This finding demonstrated that the meaning of the words, in fact the message itself, is still parsed by the participants even though they did not focus their attention on that message stream. Moray also noticed this phenomenon anecdotally in the context of the cocktail party problem: while conversing with someone at a cocktail party, and even though not paying attention to the neighbors' conversations, one can still effectively perceive his/her name if it is mentioned in the unattended neighbors' conversation. Such observations led Treisman (1960) - Prof Broadbent's PhD student - to propose an alternative theory of how attention functions: "*the attenuation theory of attention*" (Figure 1.1.B.). According to Treisman, unattended information is not totally blocked out of the "information processing system" (*i.e.*, as Broadbent's filter theory postulated) but is only attenuated[12], explaining why humans are sometimes able to extract the meaning of unattended information. In this sense, one may consider Treisman's attenuation theory of attention as an evolution of that of Broadbent. Both Broadbent's and Treisman's theories are commonly called "*early selection theory of attention*" as they both assume that the attention-related selection of the information to be processed takes place at an early stage in the information processing system.

Contrary to Broadbent's and Treisman's theories, the "*late selection theory of attention*" (Figure 1.1.C.) proposed by Deutsch and Deutsch in 1963, asserted that "*preattentive vision [or audition] perceptually analyses the entire scene to a high level,*

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[12] Interestingly, if one dwells on the computational metaphor, both Broadbent's and Treisman's theories could be considered as filter-based: Broadbent actually talked about what is called an "*ideal filter*" in electronic engineering (*i.e.*, a theoretical filter that completely eliminates all frequencies above or below the cutoff frequency) while Treisman's ideas more reflect the concept of a "*practical filter*" (*i.e.*, a filter in which there is some roll-off rate based on the order, allowing to attenuate the frequencies above or below and close to the cut-off frequency).

including identification of objects. Attention then selects a subset of this highly processed information for further analysis and response planning" (Kanwisher and Wojciulik, 2000). Thus, the difference between this theory and those of Broadbent's and Treisman's resides in where the selection process takes place in the sensory information processing system or, in other words, up to which stage in this system the unattended information is processed. It is striking that Deutsch and Deutsch's late selection theory of attention – in the same way as Treisman's theory – describes convincingly Moray's observations regarding perception of the unattended words semantic meaning. However, both behavioral (*e.g.*, Lachter et al., 2004) and early neuroimaging (please see Kanwisher and Wojciulik, 2000, for a review) findings seem to confirm the former and cast doubt on the latter.

Schematic arrows-and-boxes representations, given in Figure 1.1, illustrate each of the three theories presented in this subsection. Overall, the main idea driven by these three cognitive theories of selective attention is that of a single channel which allows attended information enter working memory for further processing and for response planning (see Figure 1.1). Accordingly, these are usually referred to as "*bottleneck theories of attention*" (Driver, 2001), referring to the way attention filters out irrelevant stimuli, either completely (*i.e.*, according to Broadbent's early filter and Deutsch and Deutsch's late filter theories) or partially (*i.e.*, according to Treisman's early attenuation theory)[13]. By reading again the *Reminder Box I*, one may notice that, following the "philosophical period", attention was considered as a process for prioritizing information. In the study of this prioritization of information, bottleneck theories mainly contribute in terms of understanding the suppression of unattended stimuli, without considering any potential facilitation of the attended stimuli. The view of attention as a facilitatory process came later, with the development of cognitive neuroscience as a discipline (please see subsection *1.3. The Neuroscience of focused attention*, p. 52).

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[13] I would then suggest that, according to Treisman theory, *inattentional blindness and deafness* do not exist by themselves. We could rather talk about inattentional "*visual and auditory partial impairment*", since all the unattended sensory information is not completely rejected.

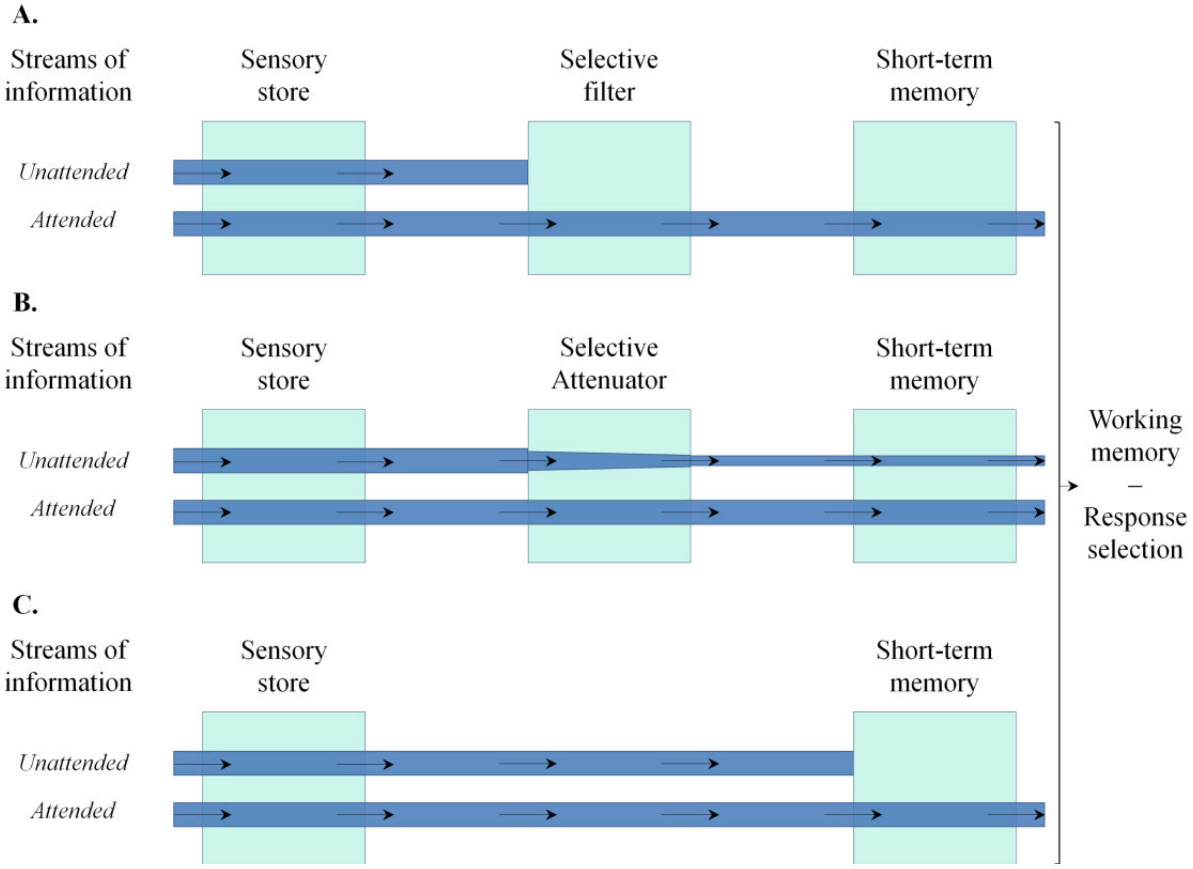

Figure 1.1: Schematic arrows-and-boxes representations of the Broadbent's (A) Treisman's (B) and Deutsch and Deutsch's (C) models of selective attention. Black arrows represent the flow of information, either unattended or attended. Boxes represent key steps of the sensory information processing system for each of the three theories.

In summary, bottleneck theories describe attention as a single-channel selective process. The next step in the history of attention research consisted of a move to a quite different conceptual framework, by considering that humans' attention can be divided through multiple channels (*i.e.*, through the process of divided attention). This conceptual shift required new theories which in time emerged and these considered attention as a phenomenon which arose from a resources-limited view of cognitive function. Some researchers considered these new - resource-based - theories as running complete counter to existing selective theories of attention (*e.g.*, see Wickens, 2002). In my opinion, these resources-based theories of attention do not preclude selective views of attention and in fact I think these theories can actually co-exist together. Rather, by taking a divergent look at the issue, the two perspectives provide complementary information on how attention functions.

1.2.3. Attention resources-based theories

"*Any man who can drive safely while kissing a pretty girl is simply not giving the kiss the attention it deserves.*" Einstein (1945).

In this famous quote, Einstein prodigiously anticipated - one more time - the way scientists were going to apprehend and define attention in the ensuing years (*i.e.*, from the early 1970s): in terms of a resources-limited cognitive function. According to the resources-based theories, focusing attention on a specific task extracts a certain **cost** manifested by one's inability to simultaneously perform another attention-related task. To keep the resources-related metaphoric jargon, one might have even said "*Any man who can drive safely while kissing a pretty girl is simply not* ***paying attention*** *enough to the kiss*", as the commonly exploited idiom "*paying attention*" relates this concept of cost.

The starting point for resources-based attention theories was the publication of a seminal paper by Moray in 1967 in which he proposed that humans' processing information system does not act as a *limited, fixed capacity channel*, but rather as a *limited capacity processor*[14]. The conceptual shift was subsequently significant: theories not only moved - as previously mentioned - from a "single channel" to a "multiple channels" view of attention in structural terms but also switched from bottleneck - purely *structural* - theories towards a more *functional* view of attention. In his book *Attention and Effort* published in 1973 based on the ideas launched by Moray a few years previously, Kahneman developed a theory of attention in which he postulated that humans possess a single pool of finite attention resources. According to Kahneman, attention resources may be distributed over multiple sources of information and might result in a competition for these resources, usually reflected as a decrement in behavioral performance in (at least) one of the tasks in which the subject is engaged (*i.e.*, as in the example of the man who drives while kissing the girl). Experimentally speaking, resources-based theories have therefore associated with divided attention-related multi-tasks protocols, a kind of experimental protocol not considered in the attention literature until this period. The following paragraph taken from Kahneman's book (p. 16) clearly highlights the linkages between the emergence of this new theory and the related novel experimental approach:

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[14] Please note again the computationalism influence on Moray's way to address the issue of attention.

> *"A measure of spare capacity can be obtained by studying the response to a probe signal, which is shown to the subject at an unpredictable time during the performance of the primary task (e.g., Kahneman, 1970; [...]). [...] a failure to identify a signal that is normally identified with ease or an unusually slow response provides evidence that spare capacity is reduced by task performance. The logic of these methods is that they indicate how much attention was deployed in monitoring at the instant of signal presentation. A failure of attention at that time necessarily causes a slowing of the response, and it may cause a failure to identify a target, if the target is removed before attention can be drawn to it.* ***Interference between tasks is due to the insufficient response of the system to demands, and to the narrowing of attention when effort is high****."*

This excerpt from Kahneman's book provides further supporting context as to how the resources-based theory of attention was initially conceived. In my opinion, it is important to note **that the resources theory of attention originally emerged in order to explain phenomena observed in the case of multi-tasking experiments, involving divided attention**, *i.e.*, while the attentional capacity at a given instant in time has to (but not necessarily succeed in) reach(ing) the "attentional demand" of the multiple tasks to be realized. The notion of limited resources is taken as the theoretical basis to explain other phenomenon such as TOT-related attention decrement, something which, to me, may have lead to conceptual errors in this context. Further relevant discussion is given in Section 2 of this chapter (please see p. 93).

Of note, one of the founding assumptions of the Kahneman's theory - conveyed by the phrase highlighted in the paragraph quoted above - was that increasing the "momentary effort"[15] to perform a given task would further decrease the behavioral performance in the other, simultaneously performed task. The possibility of modulating in a gradual manner the attentional engagement illustrates very well the distinction between resources-based theories and the "*all-or-nothing*" bottleneck theories. My earliest research on attention provided evidence which supported Kahneman's assumption and, in so doing, further reinforced his

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[15] To Kahneman "*momentary effort*" and "*momentary attention*" are interchangeable in the context of his theory (please see p. 13 of his book, *Attention and Effort*).

whole theory. In one of my studies, the very first aim was to better understand the relationship(s) between changes in cognitive workload and changes in related brain activity (published as Mandrick et al., 2013a [16]). The results of this study can however be complementarily interpreted in the light of the Kahneman's theory of attention and represent, to me, a compelling support for the previously mentioned assumption. These results are presented below. The full paper publications can be found in the Appendices section (Appendix A).

In this study, fifteen subjects realized a dual-task involving *(i)* a visuo-guided handgrip task performed either at 15 % or at 30 % of maximal voluntary contraction (MVC) and *(ii)* a mental arithmetic (MA) task. The instruction given to the subjects during the handgrip task was to match the level of force produced with a visual target (representing the expected level of force) displayed as a line on a screen. Given the linear relationship between force variability and force production (Missenard et al., 2008), we assumed that performing the handgrip task at 30 % of MVC, as compared to realizing it at 15 % of MVC, might require more attention-related motor control (Näätänen, 1992) to match with the visual target[17]. The MA task consisted in sequential subtractions of two-digits numbers from four-digits numbers. The task duration was of 60 seconds. Mean force variability and MA task performance were measured over the course of the task for each possible dual-task combination as well as for the single task condition (*i.e.*, handgrip alone or MA task alone). Results are presented in Figure 1.2.

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[16] Mandrick K, Derosiere G, Dray G, Coulon D, Micallef JP, Perrey S. (2013a). Prefrontal cortex activity during motor tasks with additional mental load requiring attentional demand: a near-infrared spectroscopy study. *Neuroscience Research,* 76, 156-162.

[17] Actually, my previous findings (published in: Derosiere et al., 2014a, *NeuroImage*, 85:471-477) strongly supported this assumption. Please refer to the full paper for further discussion on this issue (Appendix B).

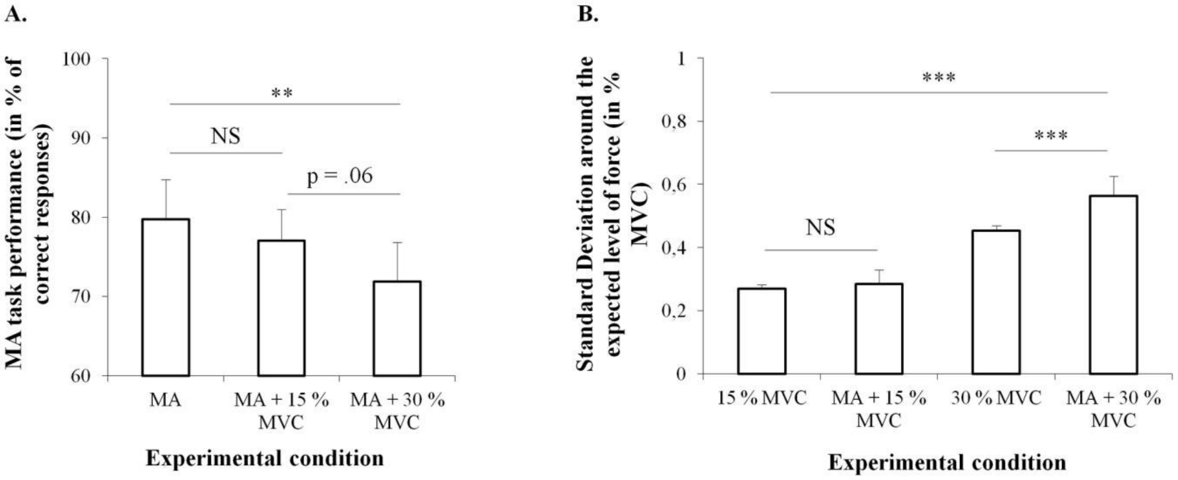

Figure 1.2: Task performance regarding the MA (A) and the handgrip (B) tasks. NS: non-significant, ** p < .01, *** p < .001. Vertical bars represent SE.

First, Figure 1.2.B suggests that, overall, realizing the visuo-guided handgrip task at 30 % of MVC did result in an increase in force variability (*i.e.*, whether the additional MA task had to be realized or not). Second, Figure 1.2.A shows that engagement in an additional handgrip task at 15 % of MVC did not result in any change in the MA task performance although the same handgrip task now at 30 % of MVC did result in a deterioration in the MA task performance. Taken together, these results clearly demonstrate that increasing the level of force to be realized in a visuo-guided task increased the need for attention resources (*i.e.*, increased force variability), which resulted in a significant decrease in the MA task performance exclusively in the 30 % of MVC condition as depicted in Figure 1.2.A. Of note, handgrip task performance also decreased in the 30 % of MVC condition (while it did not in the 15 % of MVC) when subjects were required to simultaneously perform the MA task compared to when this task was omitted. This further supports the idea that a distribution of limited attention resources model best describes this dual-task condition. In summary, the findings of Mandrick et al. (2013a) clearly illustrate Kahneman's fundamental assumption that : "*Interference between tasks is due to the insufficient response of the system to demands, and to the narrowing of attention* ***when effort is high*****".** Finally, this study represents a good illustration of the paradigm that was initially associated with resources-based theory, *i.e.*, the multiple tasks paradigm.

What Kahneman's theory did not however explain in its initial form was people's ability, in some cases, to perfectly divide their attention between two or more tasks at the same time, without any decrement in behavioral performance. Wickens (1976) and Kantowitz and Knight (1976) were the first to bring experimental evidence of such a phenomenon (for an early meta-analysis of such experimental findings please see Wickens, 1980, 1984). This was then the starting point of an evolution of Kahneman's theory towards a multiple resources theory of attention - primarily developed by Wickens (please see Wickens, 2002; 2008, for review). The multiple resources theory states - as its name suggests - that attention resources do not form a single pool but are rather composed of separate multiple pools of resources. Accordingly, decrement in behavioral performance in dual-tasking can only occur if both tasks involve resources allocated from the same given pool among the multiple pools defined. Results from an experiment reported by Parkes and Coleman (1990) clearly show how divided attention can be functionally understood through reference to a multiple resources theory perspective. In that instance, the authors demonstrated that driving while engaged with a reading task causes powerful interference effects to emerge - as demonstrated by a significant deterioration in behavioral performance for both tasks. Further, driving while listening to the same information did not result in any interference (*i.e.*, in the experiment, the information to be listened was the same as the one that had to be read in the first condition). According to the multiple resources theory, in the first situation behavioral performance diminished as each task demand competed for visual attention resources. Contrariwise, in the second situation, driving mainly required visual resources while listening required auditory resources, explaining why interference did not occur. Of note, the dichotomy between auditory and visual resources described here was not the only one within the multiple resources theory - Wickens (2008) actually defined three main dichotomies[18]. He represented these three dichotomies within a 3-dimentions cube, represented in Figure 1.3. Further information regarding these dichotomies is given in the legend of Figure 1.3.

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[18] There are actually three main dichotomies in the last model proposed by Wickens (2008). However, the early formulation of the theory did not clearly stipulate these. As described by Allport (1989), the multiple resources theory has been further developed after its initial formulation in the late 1970s by adding supplementary potential types of resources - and related dichotomies - in the model each time a new type of interference was demonstrated.

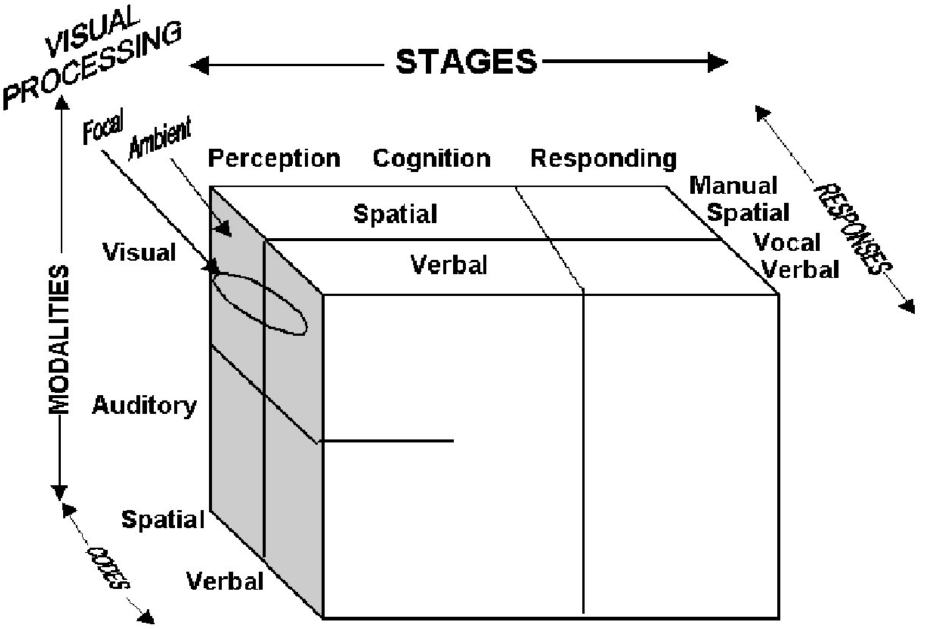

Figure 1.3: Wickens' 3-dimensions cube representation of the multiple resources theory of attention (from Wickens, 2008). The three main dichotomies given by Wickens are represented by the three dimensions of the cube. The first - the *modalities dimension* - is the one previously mentioned in the text and states that visual and auditory perception use different attention resources. The second - called the *stages of processing dimension* - illustrates that cognitive (*e.g.*, memory) and perceptual stages do not exploit the same resources than the selection and execution of action stages (Isreal et al., 1980). The last, named the *codes of processing dimension* - describes that spatial activity and verbal/linguistic activity do not use the same resources, this dichotomy having been experimentally verified in working memory, perception (*e.g.*, Baddeley, 1986), as well as action (*e.g.*, speech versus manual control; Wickens and Liu, 1988). Finally, two sub-dimensions were added to the visual processing dimension in order to take into account the distinction between focal (*i.e.*, mainly foveal) and peripheral vision.

While the multiple resources theory of attention is appealing at first sight because it facilitates explanation of experimental cases where no interferences occur between two tasks performed simultaneously, it does however presents more difficulties when trying to explain situations where interference did occur even though both tasks did not appear to engage the same resource pools as referenced by the previously mentioned dichotomies. Consider again, for instance, the results from Mandrick et al. (2013a) presented above (see Figure 1.2, p. 44) and try to project the respective resources related to both tasks within the Wickens' 3-dimension cube (please see Figure 1.4, hereafter).

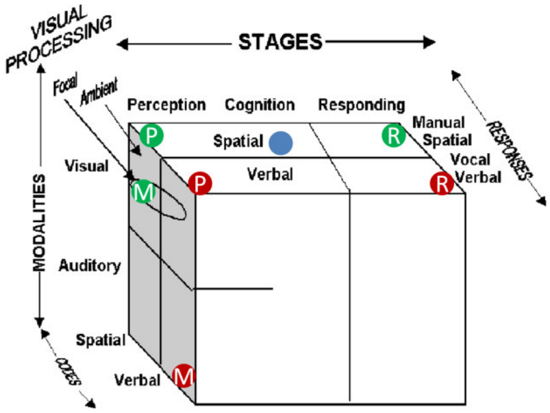

Figure 1.4: An attempt to interpret the results from Mandrick et al. (2013a) based on the multiple resources theory. Green circles represent the main resources engaged in the visuo-guided handgrip task while red circles represent the main resources engaged in the MA task. M: Modality-related resources; P: Perception-related resources; R: response-related resources. Regarding the visuo-guided handgrip task, the modality was visual, perception can be qualified as spatial, and the "response" to that visuo-spatial stimulation was manual. In contrast , the modality and perception were verbal and the responses were given verbally in the MA task. Thus, this illustration demonstrates that there should have been no interference between the multiple pools of resources when performing the two tasks simultaneously. However, there was an interference effect as reflected by the decrement in behavioral performance in both tasks (please see Figure 1.2, p. 44). The only way to interpret such results in the context of the multiple resources theory would be to search for other resources that may have been shared between both tasks. The blue circle represents this potential shared pool of resources in the case of the results of Mandrick et al. (2013a). One could suggest that the cognitive processing associated with the MA task could have involved some visuo-spatial aspects potentially related to the representation of the numbers. Through this line of reasoning, Lee and Kang (2002) suggested that subtraction tasks involved visuo-spatial processing functions.

To sum up, the multiple resources theory explains a greater range of experimental data than the Kahneman's "*single pool of resources*" theory in the case of divided attention. Nonetheless, it is worth pointing out that the multiple resources theory does not challenge the basic assumptions of Kahneman's theory. These assumptions postulate that **attention resources are limited at a given instant in time**[19] and that, accordingly, **increasing the attention demand related to one task further decrease the behavioral performance in the other task** if performed simultaneously. Aside from their purely cognitive psychology-based theoretical definitions, neurophysiological substrates have been provided to support the concept of attention resources in the case of divided attention[20]. These neurophysiological substrates are briefly mentioned in Section 2 of the current chapter (please see pp. 97-100). The *Reminder Box II*, hereafter, synthesizes the main ideas provided by early cognitive psychologists on attention (*i.e.*, from the early 1950s to the late 1980s). Also, in the late 1980s, based on the past 40 years of research, some authors have proposed to distinguish several components of attention (*e.g.*, Posner and Rafal, 1987). The definition given by these

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[19] Indeed, Wickens' theory also postulates that there are limited attention resources at each instant in time, but Wickens added to Kahneman's theory that these limitations are to be considered regarding each single pool among the multiple pools of resources.

[20] I emphasize here "*in the case of divided attention*" since, as we will see later, there is currently no empirical neuro-physiological evidence supporting the limited resources theory in the case of the attention decrement phenomenon, in which the limitation of attention resources are evoked in a completely different way (please see Section 2).

authors contributed to synthesize the conceptual advances that had been made regarding the definition of attention until this period. I thus present these synthesis works in the next subsection.

Reminder Box II

Unattended stimuli are suppressed and attended stimuli are processed through a single-channel in the information processing system (Broadbent, 1958; Treisman, 1960; Deutsch and Deutsch, 1963).

Attention can be divided among multiple channels (Moray, 1967).

Attention is limited in a single pool of resources: divided attention leads to decrement in behavioral performance (Kahneman, 1973).

Attention is composed of multiple resources: divided attention leads to decrement in behavioral performance if the several performed tasks require the same type of attention resources (Wickens, 1980).

1.2.4. Late 1980's: definition of components and subcomponents of attention

The first account of a subdivision of attention within distinct components was actually provided in 1971, by Posner and Boies. The authors distinguished two "*intensity components*" of attention: phasic alertness and vigilance. While the concept of vigilance has been recognized since the late 1940s through Mackworth's investigation (see p. 36), phasic alertness protocols had been only recently developed at this time to study short-duration focused attention (*e.g.*, in Bertelson, 1967; Posner and Wilkinson, 1969). Phasic alertness is commonly defined as the ability to "*increase response readiness [and preparation for an upcoming stimulus][21] for a short period of time subsequent to external cues*" (Sturm and Willmes, 2001). It is in this context that phasic alertness has been distinguished from vigilance, which is - in contrast - related to maintaining attention over time (see below for a more precise description of the concept of vigilance). The idea of different intensities of attention has also been explored by Kahneman during the same period (1973) in the

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[21] Brackets added.

introduction of his book. Kahneman remarked that, for him, attention was not a "*all-or-nothing*" cognitive function. Regarding the "*selectivity components*" of attention, Posner and Boies (1971) concentrated on the description of focused attention only - as the works on divided attention were just burgeoning at this time (see pp. 41-48). Posner and Rafal (1987) and Van Zomeren and Brouwer (1994) later further developed the definitions given by Posner and Boies in 1971 by considering both intensity and selectivity components of attention, including then divided attention. Figure 1.5 illustrates the distinct components of attention according to these authors.

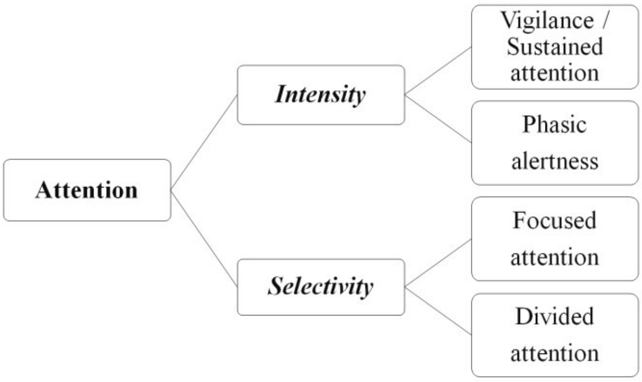

Figure 1.5: Schematic representation of the different components and subcomponents of attention as defined by Posner and Rafal (1987) and by VanZomeren and Brouwer (1994). This representation synthesizes the main advances made in research in cognitive psychology regarding attention definition from the early 1950s to the late 1980s. The subcomponents defined within the intensity and the selectivity components are not exclusive at all, but are necessarily combined, as it can be observed in the design of the experimental tasks. For instance, focused attention and divided attention can be investigated in both phasic alertness and in sustained attention conditions.

The current subsection summarizes the main theoretical advances made in cognitive psychology up until the late 1980s as regards to *how* attention could be deployed (*i.e.*, in phasic, sustained, focused or divided ways). Another issue arose in the late 1980s which concerned as to *what* attention could be directed to (Requin, 1985). Attention can indeed be phasic, sustained, focused or divided, but in all these cases attention may not necessarily be directed to the sensory world - as we described in the previous subsections. Attention may also be directed to action, Requin stated. The next subsection brings further precision on the emergence of the investigation of what has been later called motor attention.

1.2.5. Towards the investigation of attention to action

> "*[...] motor theories of cognition [...] fell into oblivion because the theoretical 'zeitgeist' of the century was input-centered and did not much care about action per se*", said Hommel (2001) about the pre-1980s period.

At this point of the manuscript, one may notice that we have predominantly addressed the issue of sensory attention (*i.e.*, attention directed to sensory stimulation). To do so, we first went through the philosophical period, in which most of the conceptual analyses were made with regards to visual attention (please see pp. 32-33). We then moved on to the early cognitive psychology research which, through the dichotic listening experiments, investigated auditory attention (please see pp. 37-40). This period bears witness to how attention was primarily considered, that is, as mainly responsible for prioritizing sensory information processing. With the book of Kanheman (1973), however, a first re-introduction of the idea of attention to actions - first evoked by Bain in 1888 and set aside until this period[22] - arose. He notably wrote "*A capacity theory is a theory of how one pays attention* ***to objects*** *and* ***to acts***" (p. 8), highlighting that, to him, attention can be focused on both sensory stimulation and motor action. According to this idea and in line with his resources theory, he predicted that as a motor skill becomes automated, it requires less attention resources for performance. Kahneman nonetheless talked about attention to actions as if it was something implicitly accepted in the cognitive psychology community at this time, while it was not necessarily the case. One key step for the realization that attention can be investigated while directed to actions was the chapter of Requin in Posner's book *Attention and Performance XI* (1985). Requin began his chapter with:

> "*Attention [...] has generally been considered, until recently, as acting upon sensory input. [...] the definitions proposed for attentional processes, [...] emphasize the role of attention in the selection of stimuli. [...], at the end of the 1970s, although several studies addressed the question of the attentional demand of movement in the frame of dual-task paradigm, no more than half a dozen papers were written under titles associating attention with movement*".

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[22] One may notice that from the 1950s to the 1970s, the topic of attention was exclusively understood through a perception-based approach. Since Bain (1888, see the first subsection, p. 34), the fact that attention can be directed to action as well was somehow forgotten.

On this basis, Näätänen (1992) proposed two types of attention which concerned actions. The first type is in the context of non-ballistic movement, which, according to him, may require a continuous attentional control throughout execution if not automated. In this case, the "*motor program*", according to the terminology usually exploited at this time, is not fully and definitively selected prior to movement execution. Instead, humans exploit attention in order to correct the course of a given movement based on subsequent sensory feedback. This is basically the "attention to action" that was involved in the visually guided handgrip task we exploited in Mandrick et al. (2013a; please see p. 44). The second type of attention to action refers to ballistic movements. In this case, Näätänen (1992) described that attention here is deployed before movement, and is used for selecting in advance the "*motor program*" to be executed. On the other side, attention cannot be exploited to correct any parameter of ballistic movements during their execution. In this manuscript, we will mainly focus on this kind of pre-movement attention. I will now exploit the term *motor attention*[23] to specifically refer to this ability. Given that, as noted in the introduction, attention decrement is known for impairing both humans' sensory and motor abilities, both sensory- and motor-related attention processes will be addressed in the subsequent subsections.

It is notable that further evidence for the existence of motor-related attention processes was later provided during the investigation of the neural basis of attention. Accordingly, detailed descriptions are given regarding the neural basis of motor attention on page 63. Let's note the significant step we are taking here: we now talk about neural substrates of attention. The switch from a cognitive psychology approach (*i.e.*, mainly based on behavioral results) to a more neuroscience-based approach represents the next step in the history of research on attention - and thus, the next step of this chapter. With the increasing use of functional magnetic resonance imaging (fMRI), of positron emission tomography (PET), and - to a lesser extent - of NIRS techniques for research purposes, the *human neuroscience* field developed rapidly following the late 1980s, bringing deeper understanding to the functioning of attention. The next section, titled *The Neuroscience of focused attention*, reports what we currently know about the neural substrates of attention, with a special focus on focused attention - either motor- or sensory-based. One may however note that, even if the knowledge in neuroscience developed more rapidly after the late 1980s because of technological advances, the investigation of the neural substrates of attention began earlier. For instance,

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[23] I exploit this term intentionally so as to make a direct link between attentional processes and motor action. The process to which I refer is also known under the terms of "motor preparation", "movement preparation", or even "action planning".

Wurtz, in the 1960s, recorded electrical signals from the brains of macaques who were trained to engage in attentional tasks. He was the first to show that there was a direct link between neural activity and a "*mental*" process. On the other hand, in humans, the development of EEG-measured event-related potentials (ERP) in the 1970s led to investigation of attention-related effects on cortical activity (Karlin, 1970; Näätänen, 1970). The review I made regarding the neural substrates of attention - presented hereafter - has therefore not been constrained to the period following the late 1980s.

1.3. The Neuroscience of focused attention

In the past 30 years, neuroscience investigation into the biology of attention has flourished in a dramatic fashion. In this section, I have narrowed my review on the neural substrates of focused attention to the most relevant aspects, as I have not investigated divided attention in my experiments (please see chapters II, III and VII)[24]. Also, note that, as I previously stipulated (please see p. 36), my aim is to provide the reader with key elements regarding *endogenously (top-down) controlled attention*, involved in sustained attention tasks[25]. Thus, the subject of this subsection does not cover the neural substrates of exogenously (bottom-up) oriented attention - which also represents a topic of widespread interest in the literature (*e.g.*, see Buschman and Miller, 2007 and Miller and Buschman, 2013, for appealing comparisons of the neural substrates of bottom-up versus top-down processes).

We have already established that attention can be focused on the given sensory information to be processed as well as on a given motor action to be performed. These kinds of focused attention involve, in part, sensory and motor cortical structures. The involvement of sensory and motor cortical structures in sensory and motor attention are presented in the first and second parts of this section, respectively. These cortical structures are what I consider as the neural sites where attention is expressed, that is, where the neural signatures of the selective process are exhibited. Describing how focused attention is expressed at these

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[24] Some information are however provided regarding the neural basis of interference phenomenon observed in divided attention tasks in the second section of the current chapter, p. 98.

[25] I do not stipulate that attention cannot be exogenously captured during sustained attention tasks, but rather state that sustained attention is a voluntary - and therefore endogenously controlled - process.

neural sites is key to a deeper understanding of the process. My goal is notably to demonstrate that, **at those input (sensory) and output (motor)-related cortical sites, focused attention is actually expressed in a very similar way.** Finally, neuroscience does usually not associate one given cognitive or motor function to one single brain area. Instead, each cognitive function must be considered in relation to a neural network. I therefore then describe the neural networks (*i.e.*, composed of several cortical and sub-cortical structures) allowing the expression of focused attention at the sensory and motor cortical sites.

1.3.1. Expression of focused attention in sensory cortices

What changes in neural activity Jevons (1871) or even Cattell (1885) would have observed if they could have measured visual cortices' activity of the subjects involved in their pioneering attention experiments[26]? How did visual attention manifest itself within the visual cortices of their participants? And what about the auditory cortices' activity during Cherry's dichotic listening experiments (1953)? According to Kanwisher and Wojciulik (2000), these two kinds of attentional task (*i.e.*, visual and auditory-based) might have involved similar neural mechanisms, even if the respective sensory cortices associated with each modality are different. It is to these neural mechanisms that I refer while talking about the "*expression of focused attention in sensory cortices*" - the subject of the current subsection. As visual attention has been by far the most studied process within the attention literature (see Carrasco, 2011) and affords the best-understood model of sensory-related attention (Miller and Buschman, 2013), I focus, in this subsection, on the expression of *focused* visual attention[27] within the visual cortices.

Visual attention can be focused on a given location in space - namely *spatial attention* - and/or on a given attribute of an object/event (*e.g.*, shape, color, motion) - namely *feature-based attention*. These two "*modes*" of focused visual attention were found to induce similar modulations of the activity in visual cortices (Bisley, 2011), suggesting that the mechanisms at the origin of the modulation for both processes are the same (Katzner *et al.* 2009). I will specifically show that two primary mechanisms underlie focused visual attention. First, based

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[26] These experiments are mentioned on p. 35.

[27] I specify here "*focused* visual attention" as several other attention-related visual processes can be distinguished and it can be assumed that there exists as many neural mechanisms as types of attention-related visual processes. For example, the actions of *(i)* anticipating or even *(ii)* realizing a shift of the gaze from a visual event of interest to another involve distinguishable attention-related visual processes.

on the past twenty pages of this manuscript showing the main theoretical contributions of the early cognitive psychologists (*i.e.*, Broadbent, 1958; Treisman, 1963; Deutsch and Deutsch, 1963), one may expect that focused visual attention involves a *suppression mechanism*, responsible for filtering out - or attenuating - unattended information. This mechanism manifests itself within sensory cortical structures through inhibitory neural activities. But more than simply suppressing the sensitivity to irrelevant (*i.e.*, unattended) visual events, focused visual attention acts also by enhancing activity of neurons specifically coding for the attended shape, color, motion or location. This focused neural facilitation couldn't have existed if the anatomical organization of the sensory cortical areas were not intrinsically very specialized. Before focusing on functional mechanisms involved in focused visual attention, I briefly recap some key points regarding the anatomical organization of the visual cortices.

1.3.1.1. Specialization is inherent and reflected in the anatomy of the visual cortices

More than thirty specialized sub-areas have been identified within the visual cortex (Felleman and Van Essen 1991) - organized within two functionally distinguishable pathways. Both pathways originate from V1 and involve several secondary visual areas (*e.g.*, V2, V3, V4): the occipito-parietal pathway - the so-called dorsal stream - bound from V1 to the rostral parietal cortices while the occipito-temporal pathway - the so-called ventral stream - bound from V1 to the inferior temporal cortex (please see Figure 1.6.A). Functionally speaking, the dorsal stream has been identified as involved in spatial perception tasks (*e.g.*, providing information for visual guidance of movement in space or the appreciation of spatial relations between objects), and is therefore described as the "*where*” pathway. The ventral stream, has been described as the "*what*” pathway since it is engaged during the process of identification of objects or objects' features (DeHaan and Cowey, 2011). This distinction between the ventral and dorsal streams reflects a first level of specialization in the visual cortical architecture. Further, even within these two pathways, areas have been found to present a certain kind of specialization. Actually, the size of the receptive fields (RFs)[28] of visual neurons has been shown to increase as one moves along the visual streams (*i.e.*, from V1 to secondary areas; Desimone and Ungerleider, 1986). The increase in the size of RFs is linked to a certain hierarchy in the processing of visual information. Thus, if one regards for

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[28] The RF of a visual neuron represents the area in space that, when a stimulus is presented within it, modifies the activity of the neuron. The fact that sensory cortices are organized based on RFs demonstrates the strong specialization of these cortices: each neuron can only respond to stimuli presented in a given region of space.

instance the ventral pathway, *(i)* the V1 area is crucial for detecting basic features of objects such as shape and orientation, *(ii)* the V2, V3 and V4 areas for perceiving whole objects and *(iii)* the temporal lobe for higher-level visual perception processes such as those involving the recognition of faces (the fusiform face area, FFA, is part of the temporal lobe and responsible for this function). This hierarchical specialization is presented in Figure 1.6.B. Also, each type of feature is coded by a specific population of neurons. For instance, the shape of a curved line presented horizontally to a subject would generate changes in activity in a specific population of visual neurons which would not be involved if the shape presented consists in a diagonal line (Pasupathy and Connor, 2002). Last but not least, visual perception of each hemispace selectively involves the contralateral visual cortical areas due to the decussation of the medial optic nerve fibers at the level of the optic chiasma[29]. Thus, perceiving events occurring in the left hemispace selectively involves the right visual cortical areas, and *vice-versa*.

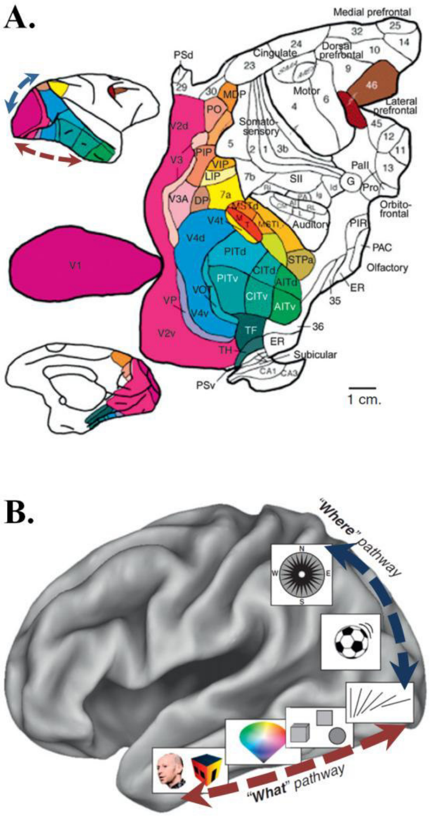

Figure 1.6: Representation of the dorsal (dark blue arrows) and ventral (dark red arrows) visual streams (both pictures are after DeHaan and Cowey, 2011). A. is a reproduction of the visual maps of the primate cortex according to Felleman and Van Essen (1991). Dorsal and ventral streams are represented on the lateral view in the top left corner. Colors indicate if areas are in the occipital (purple and blue), the parietal (orange yellow and light brown), temporal (green), or the frontal (brown) lobes. The right drawing evidences the variety of sub-areas present within the visual cortex. **B. provides a clear picture of the specialization present in each stage of the hierarchical dual pathways of vision.**

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[29] Even if certain visual neurons have been identified as possessing bilateral RF (Pigarev et al., 2001).

There is therefore a strong specialization of each of the defined sub-areas of the visual cortex, which holds the potential for selectivity in visual perception[30]. Focused attention, "*exploits*" this segregation of neural function, and facilitates the activity of population of neurons involved in processing the attended event while inhibiting the activity of those either *(i)* not involved in processing the attended stimulus or *(ii)* coding for unattended stimuli.

1.3.1.2. Neural facilitation in focused visual attention

Neural signatures of focused sensory attention can be identified in the period before the occurrence of a forthcoming target stimulus. Long-lasting increases in neural activity during the preparation for an upcoming, pre-defined, sensory stimulus were first reported in audition research by Fuster and Jervey, in 1982. A few years later, in vision research, Fischer and Boch (1985) monitored the single-unit activity of the dorsal V4 area in monkeys performing a focused visual attention task. Monkeys had been learned and were instructed to focus their visual attention on the center of a screen while ignoring the occurrence of peripheral distracter stimuli. Both the center of the screen and the peripheral stimuli were presented in the RF of the recorded dorsal V4 neurons. The authors found that when monkeys focus on the center of the screen certain dorsal V4 neurons increase their firing rates as compared to the baseline level. This increase in neural activity was interpreted by the authors as the neural signature of a facilitation process associated with focused spatial attention. Nonetheless, Fischer and Boch (1985) did not determine which neurons exhibited increased activity while focusing attention, and especially whether those had a higher response to stimuli presented in the center of the screen than in any other location. Later on, Luck et al. (1997) resolved this issue. In their study, the authors first identified neurons from dorsal V2 and V4 areas which responded to stimuli presented in a pre-determined part of the screen (*i.e.*, defining then these dorsal V2 and V4 neurons' RF). They then additionally determined topographic preferences of these pre-selected neurons[31]. During the task, monkeys were instructed, by means of a cue stimulus, to attend for a given area of the defined RF (*e.g.*, the bottom right area of the RF). They found that the neurons identified as responsive to this area

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[30] In fact, one may consider either *(i)* that this strong specialization present within visual cortices allows for focused attention to act or *(ii)* that this strong specialization might be a consequence of the need for focusing attention that emerges throughout evolution and/or development. This is a "chicken or the egg" problem.

[31] That is, they defined for instance neurons presenting a higher response when target stimuli appear in the bottom left area than when those appear in the top right area of the RF.

of the RF selectively increased their firing rates, even if the target stimulus never appeared. This compellingly demonstrates the selectivity of the facilitation process associated with spatial attention, and in particular that this selectivity can operate even when two stimuli are presented within the same RF. Results from these animal studies on spatial attention have been further reinforced by neuroimaging studies in humans, notably on feature-based visual attention. For instance, Kastner et al. (1999) found an fMRI-measured increase in the ventral extrastriate visual areas' activity contralateral to the side of the screen where subjects were instructed to covertly[32] focus on while attending for pre-defined objects (presented in Figure 1.7). This result has been interpreted as a facilitation of the activity of the contralateral visual areas, in preparation for the upcoming target stimulus. Further, it is worth noting that this "*facilitation*" occurred in the ventral stream, which is known mostly for its involvement in feature-based attention (p. 54). However, strikingly, some increased activity was measured in the extrastriate areas of the dorsal stream as well in this spatial attention study. Similarly, Giesbrecht et al. (2003) found that parts of both the ventral and the dorsal extrastriate areas were activated by both feature-based and location-based focused visual attention. As discussed by Kastner et al. (1999), these seemingly counter-intuitive results can be explained by *(i)* the requirement in the spatial attention condition to attend for a given, strictly defined visual stimulus, thus requiring feature-based attention as well; and *(ii)* the requirement in the feature-based condition to focus on a given, strictly defined visual area, thus requiring spatial attention as well. Consequently, feature-based and location-based (spatial) attention are thoroughly separable in a single task.

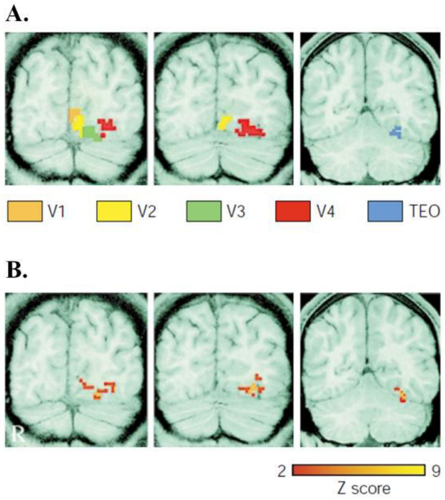

Figure 1.7: Selective fMRI-measured activation in target-related sensory cortices (after Kastner et al., 1999). A. Areas in the visual ventral stream activated when pre-defined target stimuli are presented in the contralateral hemispace. Maps were contrasted with cerebral activity during blank presentation (control condition). TEO: temporo-occipital area. **B. Areas in the visual ventral stream (same slices than in A) activated when one attends for the same object as presented in condition A, at the same location.** This activity was present even in the absence of presentation of the visual target stimulus. These fMRI results clearly demonstrate that object-based focused visual attention increase in the activity of visual areas related to the processing of the defined objects.

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[32] As previously mentioned (please see p. 34), covert attention represents the process of focusing visual attention in space, without moving the eyes, and then the locus of the gaze.

Finally, Corbetta et al. (1990) demonstrated an increase in baseline neural activity when attending for specific features (Corbetta et al., 1990). Corbetta et al. (1990) used, the PET technique and instructed participants to focus their visual attention on several attributes of presented stimuli: shape, color or velocity. They found increased rCBF - that is, increased neural activity - in areas corresponding to the ventral V4, ventral V2 and dorsal V2/V3 when subjects attend for shape, color and velocity, respectively. This represents a significant result since ventral V4 is known as strongly involved in object recognition, ventral V2 in processing more basic attributes of objects, and dorsal V2/V3 in processing movement of objects in space (please see p. 54). In sum, in this study, attention selectively increased the neural activity in each of the visual areas known as specialized in processing the pre-defined attributes of objects, before these attributes appeared at the screen. Such pre-stimulus increases in *(i)* the tonic neural firing rate of visual neurons in monkeys and in *(ii)* the PET and fMRI-measured activity in visual cortices was termed *baseline shift* (*e.g.*, Kastner and Ungerleider, 2000).

It is important to highlight that focused visual attention does not manifest itself through changes in *pre-stimulus* visual areas' activity exclusively. In fact, larger visual evoked neural activations have been observed *in response to* attended stimuli as compared to in response to unattended stimuli (please see below). It was then suggested that the previously mentioned pre-stimulus baseline shifts play the role of an "amplifier" on the activity of the visual areas responsible for processing target stimuli (*e.g.*, Kastner et al., 2000; Hopfinger et al., 2000). This led to the conclusion that focused attention acts as a "sensory gain mechanism"[33] (Hillyard et al., 1998). In the previously mentioned monkey study of Luck et al. (1997), higher dorsal V2 and V4 neurons' responses (*i.e.*, in terms of firing rates) have been recorded for instance when stimuli appeared at an attended location of the RF as compared to when the given location was not the object of focused attention. Similar results were reproduced in a number of animal studies (*e.g.*, Connor et al., 1997; Motter, 1993; Spitzer et al., 1988; Williford and Maunsell, 2006). In humans, one appropriate manner to investigate such focused attention-related neural response enhancement consists in using ERP measurements - also named VEP when recorded at the occipital electrodes and generated by visual stimulus presentation. ERP has been defined as "*a series of transient post-synaptic responses of main pyramidal neurons triggered by a specific stimulus*" (Pfurtscheller and Lopes Da Silva, 1999). A compendium of studies has demonstrated higher amplitudes of the

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[33] Here we come again with a computationalist metaphor. Then, if one would have to define *focused attention* at this point of the manuscript, in computationalism terms, it is a gain combined to a filter.

early VEP components (*i.e.*, so-called P1 and N1 waves - occurring between 80 and 130 ms) in response to attended stimuli as compared to unattended stimuli (*e.g.*, Clark and Hillyard, 1996; Di Russo et al., 2002; Heinze et al., 1994; Hillyard et al., 1998; Mangun et al., 1993, 1998), sometimes associated with a decrease in their latencies (Di Russo et a., 2002). Increases in amplitudes of these early components mostly represent an enhancement of the neural response in extrastriate secondary visual areas (*i.e.*, where the neural sources of the P1 and N1 components have been located; Di Russo et al., 2001, 2003; Mangun et al., 1997; Martinez et al., 1999). The decrease in latency observed by Di Russo et al. (2002) might reflect a faster rate of transmission of neural signals from the retina towards the visual cortices.

To sum up, focused visual attention manifests itself in the pre-stimulus period as *baseline shifts*, occurring selectively in neurons involved in the processing of the upcoming target stimulus. Pre-stimulus *baseline shifts* in neural activity then operates as a gain on the neural response to the target stimuli (Hillyard et al., 1998), thereby increasing the signal-to-noise ratio in favor of the prime pathways (involved in processing target stimulus). But there are two ways for increasing signal-to-noise ratio: increasing the signal (*i.e.*, what we have described in the current subsection) and/or decreasing the noise. In the case of focused visual attention, both processes operate together (Kanwisher and Wojciulik, 2000). How attention decreases the "noise" at the neural level is the object of next subsection.

1.3.1.3. Neural inhibition in focused visual attention

The "noise" in focused visual attention tasks is represented by the distracter stimuli that have to be ignored. At the neural level, the focused attention-related filtering of irrelevant, distracting, information takes the form of inhibitory activities. One particular well-identified type of inhibition in the brain is lateral or surround inhibition. Blakemore et al. (1970) first described the physiological mechanism of center-surround inhibition in the visual system: it allows for perceiving with more discrimination a particular object (or location) by increasing the activity of neurons responsible for processing the given object (or location), while inhibiting the activity of surrounding cells. A center-surround organization has been notably described in pools of neurons related to certain given RF such as the processing of objects falling inside these RF is facilitated because of increased excitatory activity within the

RF-related neurons, while the processing of objects falling outside these RF is suppressed because of increased inhibitory neural activity in surrounding neurons (Cavanaugh et al., 2002). Accordingly focused visual attention has been demonstrated as systematically increasing the inhibitory activity surrounding RF-related pool of neurons in the middle temporal (MT) secondary area during the pre-stimulus period (Anton-Erxleben et al., 2009; Anton-Erxleben and Carrasco, 2013). Increased inhibition has also been observed at a more macroscopic level, using for instance EEG measurements. A typical EEG-measured marker of the level of inhibition is the oscillatory activity in the alpha band (8 - 13 Hz): increased power in the α-band (*i.e.*, α-synchronization) depicts increased inhibitory activity in a given scalp area (Foxe and Snyder, 2011; Jensen and Mazaheri, 2010). An example of such an α-band-reflected inhibition comes from the study of Kelly et al. (2006). In this study, two flows of letters were visually presented to the subjects simultaneously - one in the left hemifield, the other in the right. Subjects were instructed to count the number of times the letter "X" appeared among one of the two flows of letters, while ignoring the other flow. Ignoring the left-sided flow induced higher level of α-activity in the right parieto-occipital area and *vice-versa*. Thus, α-synchronization reflects an active suppression mechanism related to spatial attention (Jensen and Mazaheri, 2010). Another study from the same group (Snyder and Foxe, 2010) reports appealing results, this time on the involvement of α-synchronization in feature-based visual attention. In this study, participants were instructed to focus either on the color or on the motion of the same presented visual stimuli. Snyder and Foxe (2010) demonstrated compellingly that focusing on the former attribute induced an α-band-reflected inhibition of motion-related visual cortical areas (*i.e.*, the dorsal stream), while focusing on the latter induced an α-band-reflected inhibition of color-related visual cortical areas (*i.e.*, the ventral stream). These results are presented in Figure 1.8 (please see next page). Thus, two kinds of *baseline shifts* occur simultaneously: the first is a push-up of the activity of neurons responsible for processing attended, target stimuli, the other is a pull-down of the activity of neurons responsible for processing ignored, irrelevant stimuli. Such focused attention-related "*push-pull*"[34] changes in neural activity would allow better detection and discrimination of the attended, target stimuli to be processed.

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[34] I refer here, based on the terminology used by Anton-Erxleben et al. (2009), to the way the activity of neurons with preference for a given visual target is pushed up, while the activity of surrounding visual neurons is pull down, when one focuses visual attention.

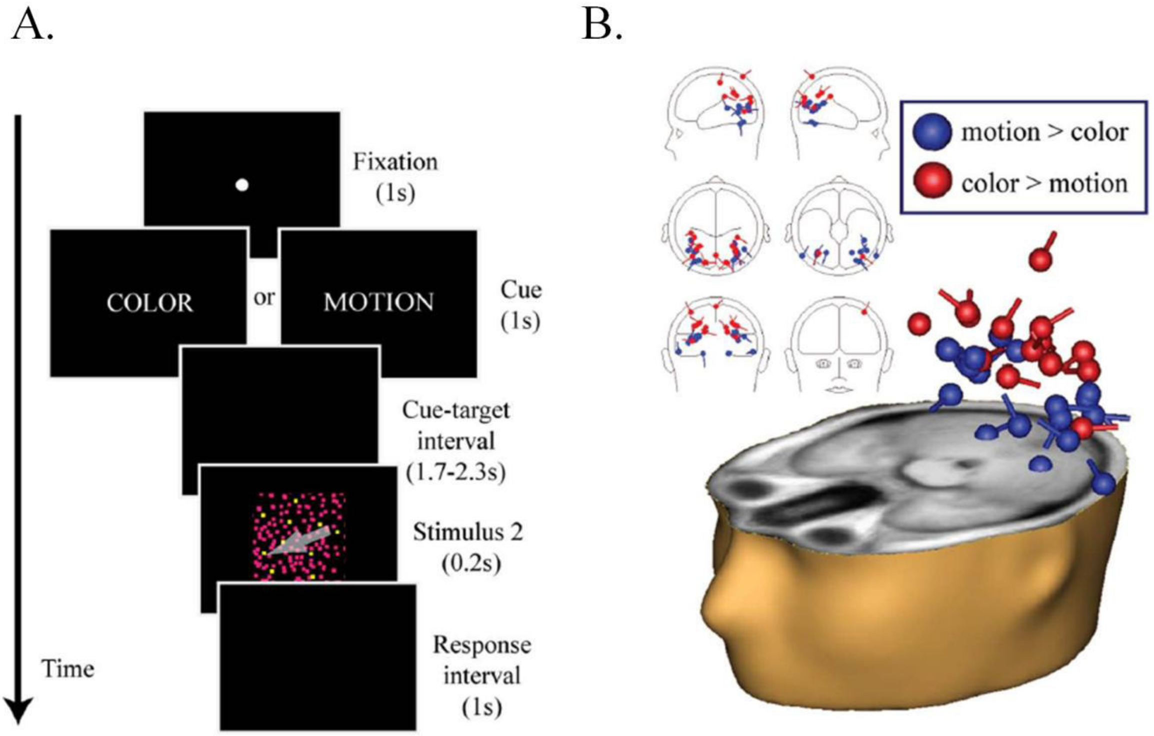

Figure 1.8: Expression of focused sensory attention through cortical inhibitory mechanisms (after Snyder and Foxe, 2010). A. Experimental task. A word cue - *i.e.*, color or motion - first indicated to the subjects the relevant feature to focus on. After a variable interval of 1.7 to 2.3 s, a random dot stimulus was promptly presented - with a fixed duration of 0.2 s. Dots were all colored and moving, regardless the condition. However, in the *motion* condition, only one color was presented (*e.g.*, pink) and some dots moved in a different direction from the rest of the dots. In the *color* condition, all dots moved in the same direction but some dots were colored in green among the pink dots (represented by the white arrow). Subjects were required to respond with a button press when they detected a target in the relevant, attended, feature among the random dot stimulus. In the other case, they had to withhold their response. **B. Source localization of the main feature-sensitive independent components in the alpha band during the cue-target interval.** Independent component analysis (ICA) was first exploited in order to separate scalp-recorded data into independent components in every subject. In red are represented components showing greater level of alpha activity when subjects attended to the color feature than when they attended to the motion feature. In blue are represented components showing greater level of alpha activity when subjects attended to the motion feature than when they attended to the color feature. Overall, the picture clearly demonstrates that ventral visual areas are subjected to higher level of alpha-reflected inhibition when ones focuses on motion, while dorsal visual areas are subjected to higher level of alpha-reflected inhibition when ones focuses on color. Focusing visual attention on one feature involves the suppression of the activity of areas unrelated to processing the given feature.

If one refers to the previous subsection, changes in pre-stimulus inhibition should be associated with changes (potentially decreases) in the stimulus-evoked response of neurons coding for unattended stimuli. This is indeed the case. For instance, in a seminal paper, Moran and Desimone (1985) described that if *(i)* two different visual stimuli are presented simultaneously in a given RF of neurons from the V4 and the inferior temporal (IT) areas and *(ii)* one stimulus is attended while the other is ignored, then "*the response to the unattended stimulus is dramatically reduced*". Monkey studies have replicated these findings for a number of visual areas from extrastriate areas V4 and V2 to striate area V1 (*e.g.*, see Treue, 2001, for review). Moran and Desimone (1985) concluded that "*the attenuation of response to irrelevant stimuli found in V4 and in the IT cortex may underlie the attenuated processing of irrelevant stimuli shown psychophysically in humans*". So, what about humans? The previously mentioned VEP results in humans (please see p. 59) not only provides evidence for facilitatory effects but also for inhibitory effects of focused attention. For instance, Clark and Hillyard (1996), Hillyard et al. (1998) and Mangun et al. (1993) found lower P1 and N1 amplitudes in response to unattended stimuli as compared to attended stimuli. However, in such studies, the reported differences in amplitudes can be the consequence of either a facilitation of the neural response to attended stimuli, or a decrease in the neural response to unattended stimuli, or even a combination of both. Indeed, the authors did not compare P1 and N1 amplitudes in response to (un)attended stimuli with their amplitudes when evoked in response to passively perceived stimuli. This was done later by Di Russo et al. (2002) who actually demonstrated that steady-state VEP (SSVEP) amplitude were higher in response to attended stimuli as compared to passively perceived stimuli and even higher in response to passively perceived stimuli than to unattended stimuli. Di Russo et al. (2002) showed similar gradual changes regarding SSVEP latencies, with the highest latency in response to unattended stimuli, and the lowest to attended stimuli. Thus, the study of Di Russo et al. (2002) demonstrates a signature of inhibitory mechanisms in the neural response to unattended stimuli in humans.

A few months ago, I presented a lecture about the neural correlates of focused attention in the lab, when someone in the audience asked me: "*So, excuse me, just to be sure: what I have learned about attention is that it facilitates, at the neural level, the processing of given, pre-defined sensory stimuli, am I right?*", to what I replied: "*Yes you are, but it is not only that. Attention also inhibits, at the neural level, the processing of irrelevant stimuli.*". He then concluded, using computational terminology: "*Oh, yes, sorry, attention is a 'plus' with a 'minus'!*". And he was right. What was however inaccurate in the answer I replied was that, by taking a sensory-based view of attention, I intimated that attention is an input-centered process by definition. It is obviously not. Motor attention is a 'plus' with a 'minus' as well, as described next.

1.3.2. Expression of focused attention in motor neural structures

> *"[...] selective mental activity or work can be observed as* ***governing motor behavior*** *in a way analogous to the role of selective mental work when we focus our mind on, that is, select, some specific type of sensory information among all concurrent sensory input*", wrote Näätänen (1992).

Focused attention not only governs our perceptions but also a large amount of our motor behaviors. The analogy between sensory and motor attention processes suggested by Näätänen (1992), Requin (1985) and their colleagues followed from the observation of behavioral data as well as from phenomenological introspection. Based on subsequent discoveries realized in neuroscience on the scope of motor attention, one may notice that sensory and motor attention present strong similarities at the neural level as well. Some key anatomical similarities between visual and motor cortices[35] have been exploited in predictive coding theories (*e.g.*, see Friston, 2005 for a review) to develop interesting discussions on potential functional similarities between vision and movement production. In a similar manner, I think that focused attention manifests itself in the same way in motor cortices during motor attention as in visual cortices during visual attention. Accordingly, I describe hereafter that, as it was the case for visual attention, motor attention works thanks to a certain specialization in motor cortices' anatomy.

1.3.2.1. Specialization is inherent and reflected in the anatomy of the motor cortices

Overall, two main functionally distinct categories of area can be discerned in the motor cortex of humans: the M1 and the secondary motor areas which consist in the PMC and the supplementary motor area (SMA). Historically, M1 has been first considered as the "*final common pathway*" for the central control of movements (Hepp-Reymond, 1988; Kuypers,

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[35] One of the main bases of the work of Friston and his team during the past five years on predictive coding in motor and sensory domains relies on the similarity of the agranular architecture in both motor and visual cortices.

1981), while the secondary areas were considered as playing a more "secondary role" in motor control, recruited upstream M1 when certain movements have to be executed. Specifically, SMA was primarily, essentially considered as responsible for the control of axial/proximal movements while the PMC area was considered as controlling more distal movements (Penfield and Welch, 1951; Woolsey et al., 1952). This simplistic view has been then revisited and detailed anatomical analyses led to the conclusion that, beyond these main characteristic traits, the secondary motor areas actually contain up to six functionally distinguishable sub-areas (*i.e.*, four composing SMA and two constituting PMC; Dum and Strick, 2002). In this vein, based on the cytoarchitectural and histochemical analyses performed by his colleague Matelli (1985, 1991), Rizzolatti wrote "*The motor cortex is formed by a mosaic of anatomically and functionally distinct areas*" (Rizzolatti et al., 1998). A mosaic of functionally distinct sub-areas can even be distinguished within M1. The so-called homunculus indeed describes how M1 is somato-topically organized, that is to say, how each given part of the M1 cortex - also called *motor field* (*e.g.*, Rizzolatti et al., 1998) - is specifically responsible for the control of movement in a given part of the body. Thus, moving the leg would involve the medial part of M1 (*i.e.*, where the motor representation of the leg has been located) while moving the fingers would involve a more lateral part of M1 (*i.e.*, where the motor representation of the hand has been located). Last but not least, moving the right hand would mostly involve the left motor cortices, while moving the left one involve the right hemisphere, and this because most of the CS tract nervous fibers follow a crossed pathway.

In summary, strong anatomical similarities can be pointed out when considering how visual and motor cortices are specialized. For instance, in visual cortices, two main specialized pathways originate from V1 and bound for the secondary visual areas (*i.e.*, the dorsal and the ventral streams). Similarly, the secondary motor areas are of two types, with the PMC specifically engaged in the control of distal movements and the SMA specifically involved in axial body movements, and both types project to M1. Furthermore, the two main visual pathways contain sub-areas, responsible for processing specific type of visual information, as the sub-areas that have been identified within PMC and SMA are responsible for controlling specific movements. It is further worth noting that, as visual neurons present a RF-based organization, M1 neurons follow a motor field-based organization. In this vein, the center-surround organization described in the sensory cortex has been transposed to the motor cortex and studied in the context of movement production (Beck and Hallett, 2011). Finally, as the information present in a given visual hemifield is well-known to be processed by the contralateral visual cortices, hemibody movements are under the control of the contralateral motor cortices. There is thus a strong specialization of each of the defined sub-areas of the motor cortex, witnessing the potential for selectivity in the control of movement. Focused motor attention "*exploits*" this segregation of the neural functions and facilitates the activity of population of motor neurons involved in producing the prepared motor action while inhibiting the activity of those not involved in producing the prepared motor action.

1.3.2.2. Neural facilitation in focused motor attention

Some of the oldest evidence for the expression of motor attention within motor cortices comes from a monkey study by Tanji and Evarts, in 1975. In this study, monkeys were trained to perform a simple movement consisting in pushing and pulling a vertical bar. M1 neurons' firing rates and movement kinematics were recorded in the period before and during the execution of movement. The authors showed that the M1 neurons specifically showing increased firing rates during the execution of a movement, also exhibited strong increases in activity in the preparatory period as compared to baseline resting-state levels even if no movement was realized during this period (please see Figure 1.9). Such a result has been then numerously repeated, and this, regarding both the M1 area and the secondary motor areas SMA and PMC (Alexander and Crutcher, 1990; Crammond and Kalaska, 1994; Kurata and Wise, 1988; Picard and Strick, 1996).

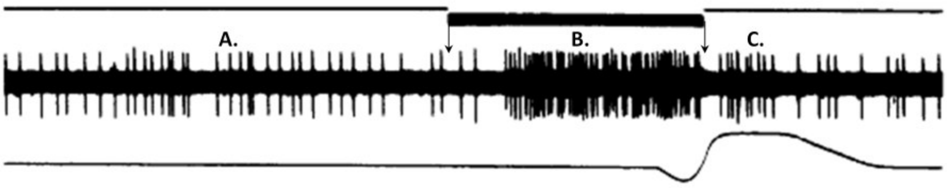

Figure 1.9: Increase in a M1 neuron firing rate during the preparation for a given movement as measured through implanted electrodes in a monkey (extracted and adapted from Tanji and Evarts, 1975). A. Baseline level of the neural firing rate. B. The left and right vertical arrows indicate the times of occurrence of cues *(i)* indicating which movement the monkey will have to produce, *(ii)* instructing the monkey to produce the given movement, respectively. The bold line at the top therefore indicates the period during which the monkey knows which movement will have to be performed (*i.e.*, which movement to focus on/to prepare). During this period a strong increase in the firing rate for the recorded M1 neuron can be observed. C. The line at the bottom represents the recorded movement kinematics. During this period the firing rate remains higher than at rest indicating the neurons engaged during the preparatory phase are the same as those engaged in the execution of the given movement.

In humans, more recent investigations on focused motor attention have been performed using the TMS technique. The TMS technique allows for investigating changes in the level of CS excitability by applying single-pulses over the M1 area and then subsequently recording motor-evoked potentials (MEP) through electromyography (EMG; Reis et al., 2008). Basically, the larger the MEP amplitude, the higher the level of CS excitability. Accordingly, a compendium of single-pulse TMS studies have found significant increases in MEP amplitudes over *the main muscles* involved in realizing the attending movement - *i.e.*, the so-called *prime mover muscles* - during the preparatory period as compared to resting-state MEP amplitudes (Chen et al., 1998; Mars et al., 2007; MacMillan et al., 2004, 2006; Van Elswijk et al., 2008). Detailed investigations have facilitated the depiction of which kind of information could be actually exploited, or could not, in order to facilitate CS excitability before the execution of a prepared movement. For instance, Mars et al. (2007) provided to their participants either *(i)* spatial-related information regarding the side of the screen where the target stimulus will appear, *(ii)* movement-related information regarding the upcoming motor response to realize, or *(iii)* no information at all. They measured both changes in MEP amplitudes and behavioral performance. Each type of information (*i.e.*, spatial-related or movement-related information) was exploited by participants as reflected by the lower RT values in these conditions as compared to the "no information" condition. However, the authors demonstrated that CS excitability increased in the prime mover muscles only when participants were provided with movement-related information. Thus, the authors concluded that changes in CS excitability specifically reflect motor attention, rather than non-specific event preparation. Further insights have been provided using another kind of TMS, namely the paired-pulse TMS technique. The paired-pulse TMS technique consists in applying a supra-threshold test-pulse preceded by a sub-threshold conditioning-pulse with a variable inter-stimulus interval (ISI) comprised between 1-5 ms and 100 ms[36]. The MEP amplitude elicited by the test-pulse is more or less decreased as compared to MEP amplitude elicited by the conditioning-pulse according to the local level of intra-cortical inhibitions (ICI). In fact, the suppression observed in the test MEP is due to the activation of short- or long-intracortical inhibitory (SICI and LICI, respectively) circuits by the conditioning-pulse (Kujirai et al., 1993). Thus, the more the conditioned-to-test MEP amplitude ratios decrease, the more the ICI circuits are recruited. Sinclair and Hammond (2008) measured the conditioned-to-test MEP amplitude ratios over the right first dorsal interosseous (FDI) muscle

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[36] The ISI duration exploited defines which type of intra-cortical inhibitory circuits - *i.e.*, short or long - is recruited.

at rest and compared the values to ratios obtained during focused motor attention. The movement having to be realized consisted in a brief right index finger flexion. These authors found that the ratios for LICI and SICI were higher during the motor attention phase than at rest. Such results evidence that motor attention acts by releasing the ICI related to the control of the prime mover muscles (*i.e.*, the FDI in Sinclair and Hammond, 2008). Also, by using longer ISI - ranging from 10 to 20 ms, it becomes possible to investigate changes in the activity of intra-cortical facilitatory (ICF) circuits (Reis et al., 2008). Using such ranges of ISI, Tandonnet et al. (2010) found an increase of the ICF as measured over the prime mover muscles (*i.e.*, Flexor Polivis Brevis, FPB) during the motor attention phase as compared to rest. Taken together, these results describe that, in motor attention, the pre-movement enhancement of the prime mover-related motor neurons' activity actually involves an increase in the activity of facilitatory neural circuits concomitant with a decrease in the activity of inhibitory neural circuits[37].

Complementary neural signatures of motor attention have been provided in humans by exploiting neuroimaging techniques. For instance, EEG-measured event-related desynchronization (ERD) have been reported over motor cortices in *(i)* either the alpha band only (Chatrian et al., 1959; Deiber et al., 2012; Pfurtscheller and Aranibar, 1977), *(ii)* the beta band only (Doyle et al., 2005; Feige et al., 1996; Gladwin et al., 2008; Pfurtscheller, 1981; Pfurstcheller et al., 1997), or *(iii)* both the alpha and beta bands (Allegre et al., 2003; De Jong et al., 2006). These ERD in the alpha and beta bands were strictly lateralized to the hemisphere contralateral to the hand involved in the required motor response. As noted by Feige et al. (1996), the observed decreases in the alpha and beta bands power can be strongly considered as reflecting a "*depression of the idling rhythms*", or, if one refers to the previously mentioned role of the alpha oscillations in cortical activity, to an overall decrease in the level of inhibition in the motor areas contralateral to the limb required to execute the prepared movement. Accordingly, the fMRI-measured blood-oxygen level depedent (BOLD) signal was found to selectively increase within the contralateral PMC (Mars et al., 2008) and M1 (Lim et al., 2010; Mars et al., 2008) areas when ones prepare for a unimanual motor response. One last relevant variable to take into account when studying pre-movement changes in neural activity within the motor cortices of humans is the EEG-measured readiness potential (RP).

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[37] Of note, I mean here that there is a decrease in the level of inhibition in motor neurons involved in the execution of the upcoming/prepared movement. Changes in inhibitory activity also occurs in the motor neurons not involved in the execution of the upcoming/prepared movement, but they manifest as increases in inhibition, as described in the next subsection.

Discovered by Kornhuber and Deecke in 1965 and firstly described by these authors as preceding self-initiated "unprepared" movements, the RP has been then depicted as lateralized (*i.e.*, namely, lateralized readiness potential, LRP) and as presenting a higher amplitude when a movement has to/can be prepared (Vaughan et al., 1968). Later on, studies have investigated how the LRP-reflected changes in motor cortices activity evolve according to the amount of movement-related information provided to the subjects (Gladwin et al., 2008; Gratton et al., 1990; Kutas and Donchin, 1980; Leuthold et al., 1996; Ulrich et al., 1993, 1994, 1998). For instance, Ulrich et al. (1998) measured the changes in amplitude of the LRP in several pre-cuing tasks with pre-cues providing advance information about either *(i)* which hand to use, *(ii)* which hand to use plus which force to apply, *(iii)* which hand to use plus in which direction to respond, or (iv) all these response parameters. They reported largest LRP amplitude when the motor response can be fully prepared thanks to a full description of the response parameters. Also, larger LRPs were linked to lower RTs, suggesting that the higher the pre-movement motor cortices' facilitation, the better the behavioral performance. Nonetheless, one of the main issues of a measure such as the LRP is that it results from the computation of a ratio taking into account both the changes in contralateral and ipsilateral motor cortices' activities. Thus, changes in LRP amplitude can actually result from an increase in the activity of motor cortices contralateral to the hand involved in the task, a decrease in the activity of the motor cortices ipsilateral to the hand involved in the task, or a combination of both. This represents a significant point if one considers that focusing motor attention on a given hand should in fact involve an inhibition of the activity of ipsilateral motor cortices, normally involved in moving the other hand. This kind of inhibitory processes is described in the next subsection.

1.3.2.3. Neural inhibition in focused motor attention

TMS studies provide some of the most convincing examples to be found in the exploration of inhibitory mechanisms in focused motor attention. For instance, Van den Hurk et al. (2007) not only demonstrated selective increases in MEP amplitudes over the prime mover muscles but also recorded strong decreases in CS excitability of the contralateral hand. Such a decrement in the central motor drive to the contralateral hand has been well-identified in the context of the execution of unilateral manual movements and results from inter-hemispheric inhibition mechanisms which would allow for impeding interference to occur between hands' movement when dexterity is required (for related discussion, please see Derosiere et al., 2014a, available in Appendix B). Then, through this process, if one focuses attention on responding to a given event with the right hand, the left motor cortices' activity would be facilitated while right motor cortices' activity is inhibited, preventing a response with the irrelevant hand. But the selectivity process associated with motor attention can be even finer, involving for instance the inhibition of muscles from the responding hand, but not those primarily involved in the to-be-produced movement. As I briefly mentioned in the paragraph on the anatomy of the motor cortices, the motor field-related organization of the M1 area might potentially allows for center-surround mechanisms to take place (Beck and Halett, 2011). In this vein, van Elswijk et al. (2008) studied the changes in CS excitability as measured over several muscles of the right hand when subjects focused on an upcoming right thumb movement. A pre-cue was used to indicate the direction in which the upcoming thumb movement was to be performed[38]. For each movement direction, the prime mover muscle was the abductor pollicis brevis (APB) as identified by the strong EMG activity in this muscle during movement execution. The EMG activities of the surrounding muscles (FDI and flexor carpi radialis (FCR)) during the production of the different movements were close to resting-state values[39]. The authors demonstrated that when participants focused on the movement of the thumb that they had to prepare, MEP values of the APB increased while MEP values of the FDI and FCR decreased significantly. These results are presented in Figure 1.10. Similar results have been produced by Beck et al. (2008). However in that case, MEP values increased over the FDI muscle and decreased over the APB muscle. Accordingly, the movement the subjects had to focus on in Beck et al. (2008) was a finger flexion. Thus, the mechanism of center-surround inhibition seems to be measurable in the preparation of different types of finger movements.

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[38] This was done because one of the aims of the authors was to investigate the relationship between changes in CS excitability and changes in the direction of the upcoming movement that subjects focused on. This parameter does not change the interpretation I make in this section.

[39] This result actually witnesses the occurrence of surrounding inhibition *during* movement execution.

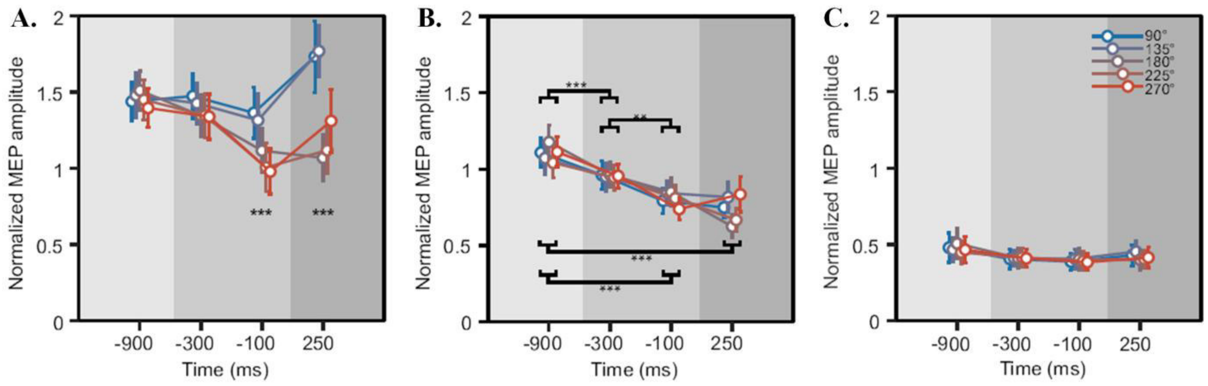

Figure 1.10: Effects of focused motor attention on pre-movement changes in CS excitability in the prime mover muscle APB (A), and two surrounding muscles FDI (B) and FCR (C) (after van Elswijk et al., 2008). MEP values were recorded at several time points during the preparatory period (x-axis). Furthermore, the subjects prepared for different movement directions, as represented by the different colors. The effects of these two factors are further discussed in the associated paper. Overall, what is interesting to notice for our current discussion is that the APB shows a large increase in CS excitability when motor attention was focused on the prepared thumb movement while CS excitability strongly diminished for the surrounding muscles.

It is worth noting that these TMS results do not necessarily reflect an expression of focused motor attention at the cortical level only. In fact, as already mentioned, changes in MEP amplitudes indicate modulations in the degree of *CS excitability*, which therefore includes both the cortical and spinal levels. Indeed, some studies have shown that focused motor attention does not solely manifest at the supra-spinal level. It transpires that similar motor attention-related changes in neural activity have been found in the spinal neurons of monkeys (Fetz et al., 2002; Prut and Fetz, 1999). These authors demonstrate, by means of implanted electrodes, that the spinal neurons can either increase or decrease their firing rates when attention is focused on an upcoming movement. They found that the direction of the changes in firing rate (*i.e.*, increasing or decreasing) during the motor attention period was the same as during the production of the prepared movement. Also, they found that two-thirds of the spinal neurons involved in the preparatory process were inhibitory. They concluded that the main role of the preparatory activity at the spinal level consists of inhibiting unwanted motor responses, or, in other terms, to filter out irrelevant motor response(s). But the increase in spinal excitability for the prime mover muscles is of importance as well and has been demonstrated many times in humans. Indeed, a compendium of studies recorded an increase in the EMG measured H-reflex amplitude, reflecting an increase in the level of excitability of the spinal neurons (Knikou, 2008), over the prime mover muscles when motor attention was focus on a given movement (Bonnet et al., 1981; Frank, 1986; Honore et al., 1982; Komiyama and Tanaka, 1990; Requin, 1969; Schiepatti, 1986). Thus, both the facilitatory and the inhibitory processes related to motor attention are expressed at the spinal level. Such changes in spinal excitability are however not dissociable from changes in motor cortical activity, the former being the structural "prolongation" of the later. In fact, it can be easily assumed that the observed changes in motor cortical activity during focused motor attention, are tightly related to those observed at the spinal level, certainly through changes in pre-synaptic excitatory and inhibitory pyramidal neurons' activities.

In summary, motor and visual attention are expressed in an analogous manner within the motor and the visual cortices, respectively. The selective process characterizing focused attention works based on, and thanks to, the very specialized anatomical organization in these similar yet divergent cortical structures. The fascinating similarities between the organization of the visual and motor cortices give rise to the operation of the suppression mechanism, so well-described in the earliest theories of cognitive psychology. In the sensory domain, this mechanism allows for the filtering out of irrelevant information while in the motor domain it impedes the production of irrelevant motor actions. Further, the neuroscience-based investigations of attention provide another substantial idea: beyond the suppression mechanism, there is a neural facilitation in favor of the target of focused attention, *i.e.*, in favor of an upcoming sensory event or of a forthcoming motor action. Focused attention is "*a plus with a minus*", regardless if it is motor- or sensory-based. Focused attention acts as a "sensory gain mechanism" (Hillyard et al., 1998), but focused attention may identically act as a "motor gain mechanism". Focused attention enhances the signal-to-noise ratio in sensory cortices, as it does in motor cortices.

Yet, strikingly, focused attention is not embodied by the same brain networks whether it is sensory- or motor-related. I previously mentioned that neuroscience does not aim at exclusively linking one given cognitive or motor function to one particular single brain structure. Rather, one must consider focused visual attention and focused motor attention as both involving a larger brain network composed of several cortical and sub-cortical structures. If one does so and extends then this view beyond the neural sites of the expression of focused attention (*i.e.*, the sensory and motor cortices), then clear divergence can be recognized between the neural correlates of the two processes. The neural networks underlying visual and motor attention are presented in the next subsection.

Reminder Box III

The visual and motor cortices are what I consider as the sites of expression of focused visual and motor attention, respectively.

Accordingly, focused visual attention manifests by a pre-stimulus increase in the activity of the visual neurons coding for the attended stimulus (e.g., Kastner and Ungerleider, 2000) and by a pre-stimulus decrease in the activity of the visual neurons coding for unattended stimuli (e.g., Snyder and Foxe, 2010).

Focused visual attention also manifests as an increase in the response of the visual neurons coding for the attended stimulus to the attended stimuli and by a decrease in the response of the visual neurons coding for unattended stimuli to the unattended stimuli (e.g., Hillyard et al., 1998).

Focused motor attention manifests as a pre-movement increase in the activity of the motor neurons coding for the prepared movement (e.g., Tanji and Evarts, 1975) and by a pre-movement decrease in the activity of the motor neurons coding for unwanted movements (e.g., van Elswijk et al., 2008).

Overall, focused visual attention and focused motor attention bear similar neural signatures, yet in distinct cortical structures.

1.3.3. Brain network for focused sensory attention

Although the previous subsection was focused on visual attention and on its expression in visual cortices, some studies have provided evidence for the theory that the neural network underlying auditory, tactile and visual attention involves common brain structures, thus composing a supra-modal network (Driver et al., 2004; Petersen and Posner, 2012). In the current subsection, I refer to this network as the *brain network for focused* *sensory attention*. This brain network is described step-by-step, through following the involvement of each single anatomical structure in the process. I start my description deep in the brain (*i.e.*, in the brainstem) and then rise up gradually towards the cortical stage. Specifically, I pinpoint how each described brain structure acts upon the sensory cortices, *i.e.*, the sites of expression of focused sensory attention, so as to produce the previously mentioned "*plus - minus*" mechanism. Please note that this literature review intends to be exhaustive regarding the structures involved in focused sensory attention but does not, however, include all currently available publications on the topic. Rather, I have selected key representative studies among the very dense literature in order to synthesize a clearer picture of this network and its actions.

1.3.3.1. Involvement of the brainstem

One specific nucleus of the brainstem, the locus coeruleus (LC), has been identified as playing an important role in focused sensory attention. The LC is well-known for being the main site for synthesis of noradrenaline (NA) in the brain and for projecting sparse pathways onto the cerebral cortex (Aston-Jones et al., 1991, 1999; Jodo et al., 1998), among many other brain structures.

Lesion studies in animals were the first to suggest a role of the LC in sensory attention. For instance, Carli et al. (1983) demonstrated that rats with lesions to the ascendant noradrenergic pathways[40] presented a decrease in the accuracy and an increase in the response latency during a five choice serial RT (5CSRT) task. The authors noticed that the increase in response latency was observed only when distracters were presented just before the target stimulus, suggesting that NA plays a substantial role in inhibitory neural mechanisms. Later on, studies measuring changes in the LC activity brought direct evidence for the involvement of this structure in focused sensory attention. Aston-Jones et al. (1991, 1999) showed, for instance, that the tonic firing rates of LC neurons in rats and monkeys rose significantly when the animals volitionally increased their level of attention to detect pre-defined target stimuli. In humans, Minzenberg et al. (2008) and Schmidt et al. (2009) found an increase in the fMRI-measured BOLD signal over the LC when subjects performed a focused auditory attention task compared to the resting state signal. Similarly, a recent study by Murphy et al. (2014)

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[40] Pathways originating from the LC and binding for the cerebral cortex.

demonstrated a higher fMRI-measured LC activity during a visual attention task when compared to resting state values[41]. Further, the increase in LC activity reported in this study was concomitant with an increase in visual cortical areas' activity. Taken together, all these results bring support to the involvement of the LC in focused sensory attention. One may then wonder how the changes in LC activity operates in concert with other brain structures, and especially, how it affects sensory cortices activity. A part of the answer was provided by Jodo et al. (1998) who demonstrated that the increase in LC activity during such tasks was ascribed to afferent links with the cerebral cortex, especially those coming from the PFC (for more details about the cortical substrates of attention, please see pp. 79-81). The proposed mechanism is the following: when *(i)* one focuses intentionally on a sensory stimulus, excitatory impulses from the PFC tend to increase LC activity; *(ii)* this increase raises the level of NA within the whole brain modifying the overall level of excitability in several neural structures; *(iii)* in the sensory cortices, NA selectively increases the baseline activity of the neurons involved in the detection of the target stimuli, while it decreases the level of excitability of neurons which are not. Accordingly, Foote et al. (1975) showed, by the mean of implanted electrodes, that a micro-iontophoretic application of NA onto the auditory cortex of rats selectively increases the activity of neurons associated with the detection of target auditory stimuli, concomitantly decreasing the background firing rates of the other cells of this cortical area. Similar findings were later demonstrated with respect to the visual cortex during visual attention tasks (Kobayashi et al., 2000; Sato et al., 1989), showing in particular that NA plays a role in the modulation of both pre- and post-stimulus neural activity. In summary, the LC-mediated NA pathway actions on the sensory cortical cells involve all the previously mentioned focused attention-related mechanisms: it pulls down and pushes up the activities of non-target-related and target-related neurons, respectively, and this, both before and in response to stimuli occurrence.

It is significant that NA-based modulation of the sensory cortices activity is not only allowed by direct pathways onto the cerebral cortex but also by indirect pathways passing through the basal forebrain (BF, Sarter et al., 2001), which itself receives projections from the cerebral cortex. The roles of the BF during focused sensory attention are detailed next.

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[41] This witnesses the supra-modal involvement of the LC in focused attention.

1.3.3.2. Involvement of the basal forebrain

The BF is comprised of a group of nuclei consisting of the nucleus basalis of Meynert, the medial septum, the diagonal band and the substancia innominata. The BF's action during focused sensory attention is mediated through cholinergic pathways mainly projecting onto the cerebral cortex (Sarter et al., 2001). Here again, lesion studies in animals have been the first to depict the involvement of this structure in focused sensory attention. For instance, Voytko et al. (1994) investigated the effects of ibotenic acid injections in the medial septum, the nucleus of the diagonal band, and the nucleus basalis of Meynert on several cognitive functions in monkeys. These BF excitotoxic lesions disrupted task-relevant attentional focusing in the visual domain. Similar results have been then found in rats (Muir et al., 1994; Bushnell et al., 1998). Further evidence that "lesions" to the BF nuclei altered focused sensory attention abilities comes from the clinical domain. Parasuraman et al. (1992) demonstrated that individuals suffering from degeneration of BF neurons as patients with senile dementia of the Alzheimer type present difficulties in focusing visual attention. Finally, in addition to the lesion studies, single-unit recordings in monkeys showed an increase in the BF neurons' activity during focused sensory attention tasks as compared to a resting-state baseline (Voytko, 1996). As a whole, this compendium of results supports the involvement of the BF in focused sensory attention.

What then are the afferent and efferent pathways related to the changes in BF activity during focused sensory attention? Firstly, as previously mentioned, afferent pathways involved in modulating BF's activity include NA linkages from the LC. Additionally, glutamatergic projections originating from the PFC have been found to have substantial effect in the modulation of the BF activity (Fadel et al., 2001). During focused sensory attention, both these afferent pathways increase the BF activity. Secondly, the BF acetylcholine (Ach)-based efferent pathway is known to terminate in practically all layers of the cortex (Sarter and Bruno, 1997), modulating the level of neural excitability. Accordingly, early animals studies demonstrated a positive relationship between BF neural activity, the release of acetylcholine within the cerebral cortex, and the level of cortical desynchronization (Casamenti et al., 1986; Détari and Vanderwolf, 1987; Szymusiak and McGinty, 1989). During focused sensory attention, the increase in BF activity induces a release in Ach over sensory cortices, which increases the level of excitability of the neurons related to the target stimuli (Herrero et al., 2008; see Figure 1.11, below), and decreases the activity of neurons unrelated to the target stimuli (Mirza and Stolerman, 2000). This double action of the Ach neurotransmitter - *i.e.*, excitation and inhibition - is mediated through its fixation on muscarinic and nicotinic receptors, respectively (Xiang et al., 1998). Figure 1.11 notably provides a compelling evidence of the role of the Ach in increasing the level of neural firing rates in cells related to the target stimuli. Thus, Sarter et al. (2005) stated that the BF actions were similar to the previously described actions of the LC on the sensory cortices.

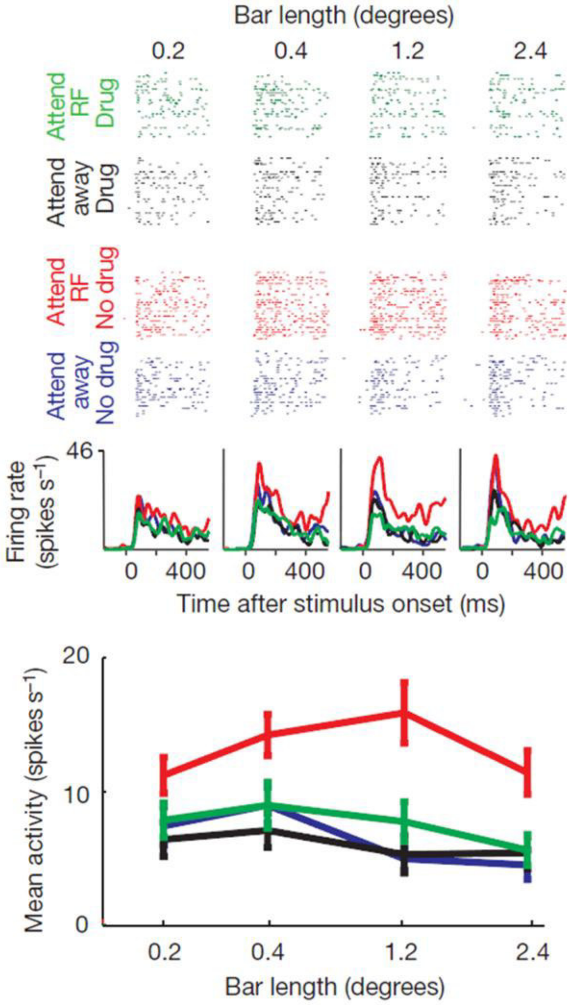

Figure 1.11: Effects of attention-related modulation of V1 neurons' responses with or without a scopolamine-induced blockage of Ach release (after Herrero et al., 2008). *Upper graph*: firing rates of V1 neurons. Four different stimuli were presented (from left to right) in four different conditions (from top to bottom). Green: monkeys focused their visual attention on the RF of the identified neurons where the target stimuli occurred. Scopolamine was applied. Black: monkeys focused their visual attention away from the RF of the identified neurons where the target stimuli occurred. Scopolamine was applied. Red: monkeys focused their visual attention on the RF of the identified neurons where the target stimuli occurred. Scopolamine was not applied. Blue: monkeys focused their visual attention away from the RF of the identified neurons where the target stimuli occurred. Scopolamine was not applied. *Lower graph*: clearly demonstrates the effect of focused attention on the increase in firing rates of these V1 neurons (in red). This effect was almost completely removed when scopolamine was applied (in green). The fact that the facilitatory effect of attention was not totally removed following the Ach blockage may result from the engagement of other attention-related brain structures as for instance the LC in the attention-related facilitation.

1.3.3.3. Involvement of the thalamus

At a coarse descriptive level, the thalamus can be considered to be comprised of four main nuclei: *(i)* the anterior, *(ii)* the medial and *(iii)* the lateral nuclei containing the thalamic relay cells which directly interact with the cerebral cortex, and *(iv)* the reticular nuclei (RN), which enfolds and projects to these relay cells through GABAergic inhibitory inter-neurons (Steriade, 2001). Both the thalamic relay cells[42] and the reticular nuclei cells have been demonstrated as having a substantial role in focused sensory attention (Brunia, 1999). Further, two main thalamus-related circuits have been proposed as being involved during tasks requiring focused sensory attention. The first type consists of a LC-thalamo-cortical circuit. However, I discuss hereafter that the involvement of this circuit in focused sensory attention lacks experimental evidence. The second type consists of cortico-thalamo-cortical loops. Its involvement in focused sensory attention is described in a second subsection.

LC-thalamo-cortical circuit: not involved in focused sensory attention

It has been proposed that the NA modulation of cortical activity, allowed by direct pathways onto the cerebral cortex and indirect pathways through the BF (please see p. 73), is also allowed by indirect pathways through the thalamus (*e.g.*, Sturm and Willmes, 2001). This assertion is based on results of Coull et al. (1997) who found that an injection of clonidine, an $\alpha 2$-adrenoreceptor agonist[43], decreased the rCBF over the thalamus. The authors found, in parallel, an increase of the perception of the effort required by the subjects to perform a visual attention task. This result was exploited in the literature (*e.g.*, Sturm and Willmes, 2001) in order to draw conclusions about a direct role of the LC-thalamo-cortical circuit in the top-down control of focused attention. However, the deactivation of the thalamus was only found at rest, and not during the execution of the visual attention task. Thus, because of the absence of any direct empirical evidence, the LC-thalamo-cortical circuit must instead be considered as mediating the level of wakefulness at rest as it had been described earlier in the literature (Moruzzi and Magoun, 1949). An initial alteration of this pathway (*e.g.*, through an injection of clonidine as in Coull et al., 1997) could subsequently lead to the requirement of a higher level of cognitive effort to focus sensory attention because of the lower level of wakefulness that it provokes.

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[42] There is actually a topographical specialization of the thalamic relay cells, such as, for instance, the posterior part of the lateral nuclei interacts with the visual cortices. For simplicity, I will however use the generic term of *thalamic relay cells* in this section without referring precisely to a specific part of the nuclei.

[43] That is, with a central function consisting in inhibiting the NA exocytosis.

Cortico-thalamo-cortical loops

In addition to the sensory cortices, two primary and anatomically segregated groups of cortical areas play a substantial role in focused sensory attention. The first group is localized rostrally in the cortex and comprises the LPFC and the anterior cingulate cortex (ACC), while the second group is localized posteriorly in the cortex and comprises several subareas of the parietal cortex (Posner and Petersen, 1990). The interaction of these fronto-parietal cortical structures with the thalamus during focused sensory attention has been largely described elsewhere (Brunia, 1999; Laberge et al; 1995, 1997; Miller and Buschman, 2013; Saalmann and Kastner; 2011; Saalmaann et al., 2012). Neuroimaging studies in humans indeed demonstrated that a number of PFC and parietal areas show increased activity in parallel to the thalamus and sensory cortices during both auditory and visual attention tasks (Frith and Friston, 1996; Lawrence et al., 2003; Sturm et al., 1999; Strum and Willmes, 2001). It is assumed that glutamatergic projections originating from the fronto-parietal network directly facilitates thalamic relay cells, which themselves in turn facilitates fronto-parietal activity through recurrent circuits (LaBerge, 2005). Significantly, such closed-loops may allow top-down attentional control to be maintained over the desired period of time (LaBerge, 2005). Finally, Brunia (1999) proposed that frontal areas excites RN cells, allowing in turn an inhibition of thalamic relay neurons and thus of sensory cortices, a loop which can participate in suppressing the activity of neurons involved in processing irrelevant sensory information.

Thus, through these cortico-thalamo-cortical loops, thalamic nuclei are engaged in focused sensory attention. But what are then the effects of such thalamic nuclei engagement on the expression of attention within the sensory cortices? In fact, thalamic nuclei may contribute to generate all the different types of attention expression identified previously (*i.e.*, both facilitation and inhibition in the forms of both baseline shifts and changes in neural response). Indeed, O'Connor et al. (2002) found *(i)* an fMRI-measured increase in visual thalamus pre-stimulus activity when subjects focused their visual attention to a location (*i.e.*, corresponding to a baseline shift); *(ii)* an increase in visual thalamus responses to attended as compared to unattended visual stimuli and *(iii)* a decrease in visual thalamus responses to unattended as compared to passively perceived visual stimuli. Pinault (2004), mostly based on anatomical and *in vitro* physiological investigations, proposed a more detailed explanation of how the neural suppression related to unattended sensory events may occur in the thalamus.

According to his analysis, focused attention first operates through a facilitation of the thalamic neurons' activity which project to sensory target-related neurons. Following this facilitation, a neural suppression of unwanted pathways is allowed through lateral inhibition mechanisms (see Figure 1.12). These suppressions in the thalamus directly modulate the level of inhibition in sensory cortices, allowing then to filter out the processing of irrelevant stimuli. Finally, it is worth noting that, in addition to the excitatory input from the fronto-parietal network, the thalamic nuclei also receive excitatory input from the sensory areas, contributing to their attentional modulation through recurrent circuits (LaBerge, 2005).

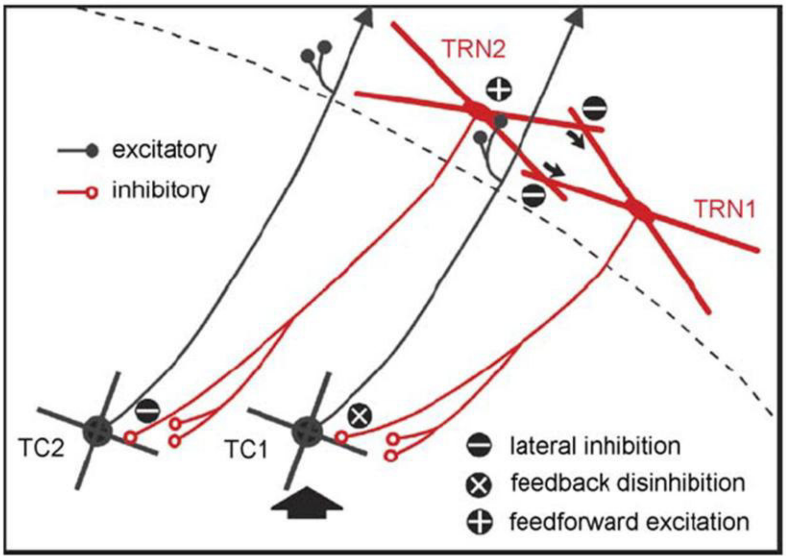

Figure 1.12: Thalamo-thalamic excitatory and inhibitory interactions related to focused sensory attention (after Pinault, 2004). TRN*i*: Thalamic reticular neuron *i*. TC*i*: thalamic relay cell *i*. These both types of cells are excitatory and inhibitory, respectively. The large black arrow at the bottom of the picture represents the excitatory input to TC1. In the case of focused sensory attention, such an excitatory input may result from a direct input from the fronto-parietal cortical network. The excitatory input is then driven towards the sensory cortices as represented by the black arrow at the top of TC1, allowing the facilitation of the neural activity related to target stimuli. Further, while crossing the RN TC1 excites TRN2 which in turn inhibits TC2. TC2 projects to the sensory cortices and the decrease of its activity would allow the neural suppression associated with ignored sensory stimuli. Finally, the increased activity of TRN2 leads to an inhibition of TRN1which then allows a disinhibition of TC1.

1.3.3.4. Cortico-cortical interactions

Beyond the above-mentioned indirect pathways passing through the thalamus, direct cortico-cortical interactions are also involved in focused sensory attention. In fact, as described by Saalmann and Kastner (2011), cortico-thalamo-cortical and cortico-cortical routes do not involve exactly the same layers of the cerebral cortex - even if they both involve common layers - and these routes can be then considered as complementary in focused sensory attention. However, both routes involve identical regions of the cerebral cortex comprised of the PFC and parietal areas (Vossel et al., 2013). In this vein, all the previously mentioned studies showing an attention-related increase in activity of the fronto-parietal areas in concert with a modulation of the sensory cortices' activity can be taken as evidence of such an interaction. Further evidence has been provided by Bressler et al. (2008) who demonstrated, by using granger causality analyses on fMRI data, a direct top-down influence of the fronto-parietal areas' activity on the visual cortices' activity during a visual attention task. Single cell recordings in monkeys have also depicted such a fronto-parietal-mediated top-down modulation of the sensory cortices' activity (Buschman and Miller, 2007; Saalmann et al., 2007). It is worth noting that these studies have also demonstrated that the top-down signal related to focused sensory attention actually originates from anterior frontal areas, and may either pass through the parietal cortices and then acts on sensory cortices, or directly influences sensory cortices activity. According to Miller and Buschman (2013) the top-down influence from the fronto-parietal areas on the sensory cortices is primarily excitatory. In this sense, the fronto-parietal operates by facilitating the activity of the neurons related to attended stimuli. The authors assumed that the neural suppression of ignored sensory information takes place subsequently, involving then local lateral inhibitory interactions, mostly through center-surround antagonism. Such a mechanism is strongly similar to that involved in the thalamus as described in Figure 1.12.

It is worth noting that the fronto-parietal areas underlying the top-down control of focused sensory attention are well-known to be strongly right-sided (Sarter et al., 2001). The dominance of the right cortical areas during tasks of focused sensory attention was firstly highlighted through the study of cerebro-lesioned patients. Posner and Rafal (1987) for instance found that patients with lesions to the cortical areas of the right hemisphere presented strong declines in behavioral performance during visual attention tasks as compared to healthy controls. These results were further reinforced by the study of Pardo et al. (1991) who found, by means of the PET technique, a significant increase of the rCBF over the right hemisphere not observed over the left hemisphere, independently of the laterality of the stimulus.

Overall, a large number of cortical and sub-cortical structures support focused sensory attention. Mediated through multiple neurotransmitters, several neural mechanisms, and either uni- or bi-directional pathways the "*brain network for focused sensory attention*" finally allows the selective processes to operate at the sensory cortical level. It is worth mentioning that the respective contribution of each of these structures is likely to be modulated, most probably depending on the task characteristics. However, one key structure has been shown to participate in the modulation of the activity of each of the other regions, in an ubiquitous manner: the anterior attention system (*i.e.*, comprised of the LPFC and the ACC). It seems that the top-down control related to focused sensory attention mostly originates from this structure. By taking the PFC/ACC as the origin of the top-down control, Figure 1.13 synthesizes all the pathways described as supporting focused sensory attention. Further, as I pointed out before the current subsection, while sensory and motor attention are expressed in a common way within the sensory and motor cortices, respectively, divergent brain networks support these two processes. The brain network for focused motor attention is presented in the following section.

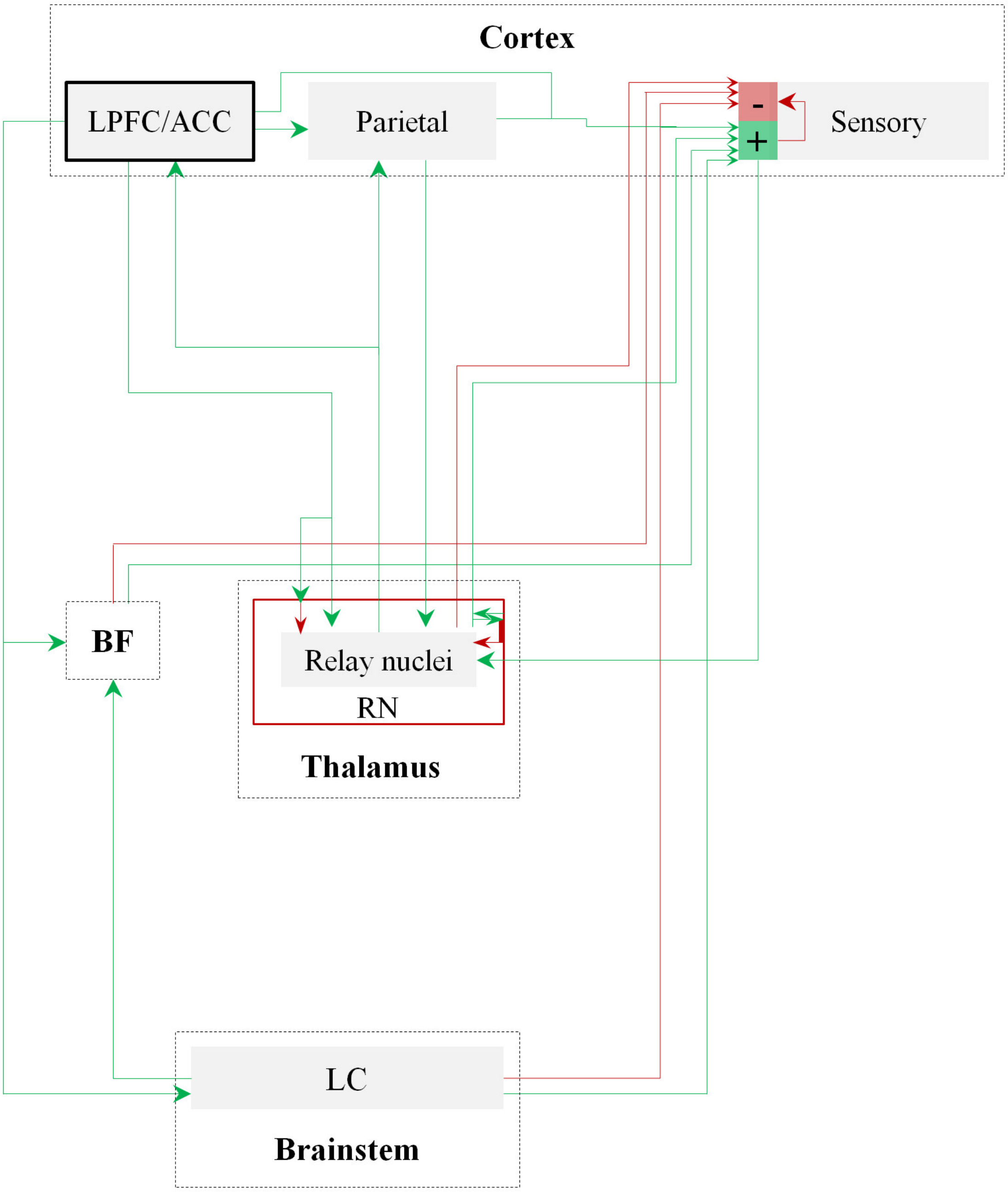

Figure 1.13: Schematic arrows-and-boxes representation of the brain network for focused sensory attention. LPFC: lateral prefrontal cortices; ACC: anterior cingulate gyrus; BF: basal forebrain; RN: reticular nuclei; LC: locus coruleus. Green and red arrows represent excitatory and inhibitory neural activity, respectively. Likewise, the green "+" and red "-" boxes represented within the sensory cortex, depict the neural facilitation in target-related neurons and the inhibition occurring in neurons coding for unattended, ignored stimuli. The red line surrounding the relay nuclei of the thalamus represents the RN. The LPFC/ACC complex is taken as the origin of the engagement of this network. By taking each structure individually and following the different afferent and efferent pathways, the reader can actually find the respective contribution of each pathway described in this subsection.

1.3.4. Brain network for focused motor attention

Probably as a consequence of the more recent interest brought into motor attention in cognitive sciences, and of the related and excessively dominant view of focused attention as primarily an input-centered process, the literature contributing to the depiction of a brain network for focused motor attention remains relatively scattered to date. Nonetheless, one particular circuitry seems to be subject to an overall agreement in the literature as regards to its involvement in motor control and, more specifically, in motor attention: the so-called cortico-striato-thalamo-cortical circuit(s). Contrary to the previous subsection on the brain network for focused sensory attention, this subsection will not be organized according to the brain architecture. Rather, given the central and almost exclusive role of the cortico-striato-thalamo-cortical circuit in focused motor attention, I will centre my description, in this subsection, on this brain circuitry. I will then describe the involvement of additional neural pathways in the motor attention process. Overall, one may keep in mind that the goal of this subsection is to provide a mechanistic explanation of evidence for the typical "*plus - minus*" expression of focused motor attention within motor cortices.

1.3.4.1. The cortico-striato-thalamo-cortical circuits as the basis of motor attention

In this subsection, I first report on evidence for the involvement of the different neural nodes comprising the cortico-striato-thalamo-cortical circuit based on lesion studies and on studies directly measuring their activities during motor attention tasks. I then describe how these different nodes operate together to support the process.

Evidence for the involvement of the basal ganglia in focused motor attention

Four principal components of the basal ganglia are involved in the cortico-striato-thalamo-cortical circuitry: *(i)* the striatum, itself comprised of the caudate nucleus (CN) and of the putamen; *(ii)* the globus pallidus (GP), which comprises internal (GPi) and external

(GPe) segments; *(iii)* the substantia nigra (SN) - pars compacta (SNc) and pars reticulata (SNr); and (*iv*) the subthalamic nucleus (STN)[44].

A compendium of studies has demonstrated the role of the basal ganglia in motor attention abilities. For instance, Rogers et al. (2001) induced quinolinic acid-based lesions to the striatum of a group of rats and compared their performance on a 5CSRT task to the performance of a control sham-operated group of animals. The authors found a strong increase in the premature response in the animals having received lesions to the striatum. A similar increase in premature, impulsive motor response has been described in rats with excitotoxic lesions (Baunez and Robbins, 1997), and with electrical stimulation-induced inhibition performed to the STN (Desbonnet et al., 2004; Frank et al., 2007). Such results demonstrate the crucial role of the striatum in inhibiting unwanted motor response, one of the prime functions of focused motor attention. It is however worth noting that, in all these studies, the appropriate motor response was produced but at inappropriate moments - that is, while no target stimulus was presented. This adds then a critical point to our previous description of the functions of focused motor attention: focused motor attention facilitates the activity of the motor neural pathways related to the to-be-executed action but this facilitation has to be constrained to a certain threshold so as to withhold the execution of the given movement in response to irrelevant events or even when no event occurs. While the suppression of unwanted motor response occurs in choice RT tasks only, the inhibition of wanted motor responses is required in choice RT tasks, recognition RT tasks (*e.g.*, Go-NoGo tasks), or in simple RT tasks[45]. Basal ganglia functions in motor attention however do not limit the withholding of the to-be-executed motor response. Baunez et al. (2001) demonstrated that the inhibition of unwanted motor responses was also strongly affected following the inhibition of STN neural activity in rats. Apart from lesion studies, some studies directly measured changes in basal ganglia activity while subjects or monkeys were engaged in a task requiring focused motor attention. In a series of studies (Alexander, 1987; Alexander and Crutcher, 1987, 1990a; 1990b; Crutcher and Alexander, 1990), Alexander and colleagues demonstrated an increase in the putamen neurons' firing rates in different experimental conditions involving motor attention processes. Others showed a strong involvement of the CN in monkeys engaged in focused attention-related action planning tasks (Hikosaka et al.,

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[44] For a more detailed description of the functional connections within these basal structures and between these ones and other structures belonging to the cortico-striato-thalamo-cortical circuit, please refer to the subsection titled *Cortical, basal ganglia, and thalamic structures acting together in focused motor attention: neural mechanisms*, p. 87.

[45] In simple RT tasks, the prepared motor response has to withhold during ISI.

1989; Rolls, 1994). Jaeger et al. (1993) recorded putamen, CN, GPi and GPe neurons' activities during a delayed RT task. Changes in neural activity was described in all these structures during the preparatory period, that is, the period during which focused motor attention was required. In cats (Cheruel et al., 1996), in monkeys (Schultz, 1986; Wichmann et al., 1994) and recently in humans (Zaghloul et al., 2012) increases in neural firing rate has been observed in the STN and SNr in similar delayed RT tasks during the preparatory period. Finally, neuroimaging studies in humans demonstrated activity increases in the putamen (Mars et al., 2008; Monchi et al., 2006), the CN and the GP (Cunnington et al., 2002; Monchi et al., 2006; Simon et al., 2002), the STN (Monchi et al., 2006) and the SN (Yanaka et al., 2009) during motor attention tasks. Thus, the involvement of the basal ganglia in focused motor attention tasks has been extensively investigated and no longer has to be demonstrated.

Evidence for the involvement of the cerebral cortex in focused motor attention

One may consider that the above-mentioned evidence that the striatum is involved in focused motor attention actually represents a first evidence for the involvement of cerebral cortex in the process. Indeed, the neural inputs to the striatum, which is itself the input structure of the basal ganglia pathways (please see p. 83), exclusively come from the cerebral cortex (Bolam et al., 2000), and changes in striatal activity imply thus changes in cortical activity. Then, what are the cortical structures precisely involved in focused motor attention? Especially, are there cortical areas involved in the process that are not motor areas, in the same way that there are some non-sensory cortical areas involved in focused sensory attention?

Yes, there are non-motor cortical areas involved in focused motor attention. And even more significantly, it seems that these cortical areas are mostly the same as those involved in focused sensory attention, involving a group of anterior (*i.e.*, LPFC and ACC) and parietal areas. This dual involvement of the fronto-parietal network has led to a major point of contention in the literature regarding its specific role in attentional processes (for related discussion, please see Petersen and Posner, 2012 and Thoenissen et al., 2002). I will not argue for an exclusive engagement of the fronto-parietal network in one of these two processes (*i.e.*, motor or sensory attention). I rather consider that this group of interconnected cortical areas may support both motor and sensory attention processes, and may even support the interaction of these two processes.

The first report of an involvement of these top-down related cortical areas in motor attention appeared with study by Fuster, in 1973. Fuster (1973) demonstrated, by means of implanted electrodes in the cortex of monkeys, that a strong and sustained increase in PFC neurons' firing rates occur during the preparation of reaching movements. Similar findings have been then provided by a number of monkey studies, regarding several sub-areas of both the prefrontal and parietal cortices (Gnadt and Andersen, 1988; Kubota et al., 1974; Niki, 1974; Niki and Watanabe, 1976; Quintana and Fuster, 2010; Rao et l., 1997; Snyder et al., 1997). Animal studies' observations have been further reinforced by neuroimaging studies in humans, which commonly described a fronto-parietal network involvement during focused motor attention (Brass and von Cramon, 2002; Deiber et al., 1996; Mars et al., 2008; Sohn et al., 2000; Toni et al., 2002).

Evidence for the involvement of the thalamus in focused motor attention

The logic taken in the previous subsection stating that the involvement of the striatum necessarily implies the involvement of the cerebral cortex in motor attention, can be followed for the thalamus as well. In fact, the contribution of the basal ganglia to the expression of motor attention in motor cortices may necessarily involve the thalamus, the thalamus being a compulsory passage point between these brain structures. One particular study compellingly established the involvement of the motor thalamus - *i.e.*, the ventral lateral (VL) nuclei - in focused motor attention (Paradiso et al., 2004). In neurological patients[46] who were implanted with deep brain stimulation in the thalamus, Paradiso et al. (2004) were able to record both VL thalamic neurons' activity and cortical activity EEG scalp concomitantly. The patients were then required to perform wrist extension movements, the execution of which was preceded by the well-known EEG-measured RP. Beyond having reproduced this cortical signature reflecting the expression of focused motor attention, the authors also observed a pre-movement increase of the local field potential within VL thalamic neurons. Further data analyses also demonstrated ERD in both α and β bands in the thalamus as well as over the motor cortices, and an increase in the coherence of these signals in the frequency domain

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[46] Patients were implanted with deep brain stimulation for treatment of tremor and myoclonus–dystonia. Deep brain stimulation electrodes also allowed to record changes in local field potentials in the thalamus.

during pre-movement period. Overall, these findings provide evidence for the involvement of the motor thalamus during a task involving pre-movement motor attention, and moreover depict an interaction between thalamic and cortical motor structures. That this study was performed in patients could all the same, represents a point of criticism. Neuroimaging studies in healthy humans have however largely supported the involvement of the thalamus in focused motor attention tasks (Deiber et al., 1996; Monchi et al., 2006; Simon et al., 2002).

Thus, together the basal ganglia, the fronto-parietal cortices and the thalamus have been demonstrated as engaged in tasks requiring focused motor attention. In the next subsection, I provide a mechanistic explanation of how these neural structures interact together within the so-called cortico-striato-thalamo-cortical circuitry during focused motor attention.

Cortical, basal ganglia, and thalamic structures acting together in focused motor attention: neural mechanisms

As highlighted by Mink (1996), in order to provide a clear picture of the functional interaction between the basal ganglia and both the cerebral cortex and the thalamus, it is first necessary to describe the structural connections between and within these brain structures. The anatomical and functional description that I provide hereafter is mainly based on the original works of Mink (1996) and Frank (2000) and, to a lesser extent, on the related work of Brunia and van Boxtel (2001) and of Gurney et al. (2001).

As previously mentioned, the striatum represents the main input structure of the basal ganglia. The striatum receives excitatory glutamatergic projections from the whole mantel of the cerebral cortex and projects to the GPi, the SNr and GPe through inhibitory GABAergic pathways. The GPi and the SNr together project to the thalamic relay cells through inhibitory GABAergic pathways, while the GPe projects to both the GPi and the SNr through inhibitory GABAergic pathways. The GPe also possesses inhibitory projections to the STN that projects to the GPi and the SNr[47] through excitatory projections. As a reminder, thalamic relay cells

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[47] As it can be observed, the GPi and the SNr are connected to exactly the same afferent and efferent pathways and have, in the context of action selection, action planning and thus focused motor attention, the same functional role. Therefore, I refer to these two nuclei under the term *GPi/SNr* in the following pages.

project to the cerebral cortex trough excitatory pathways. Finally, the SNc receives inhibitory projections from the striatum and bound in turn to that structure through both excitatory and inhibitory projections.

In the context of focused motor attention, the proposed mechanisms are the following (please see Figure 1.14 for more details). When a person focuses attention to a specific upcoming movement to execute, the fronto-parietal network is first engaged. Some authors have proposed the frontal node of the network (*i.e.*, the LPFC and ACC) as the source of the top-down attention control in focused motor attention, (*e.g.*, Brunia, 1993, 1999; Brunia and Van Boxtel, 2001), in the same manner as it was described with respect to sensory attention (please see p. 81). Spike field coherence analyses indeed confirmed that during motor attention lateral frontal cortices drive parietal cortices activity (Andersen and Cui, 2009). The action of the fronto-parietal areas results in sending excitatory inputs to the striatum. This facilitation of the striatum will lead to two main effects. First, this generates an increase in the inhibition of certain neurons of the GPi/SNr. The GPi/SNr having an inhibitory effect on the thalamic relay cells' activity, this therefore engenders a disinhibition of the thalamic relay cells, and leads finally to a facilitation of the desired cortical motor neurons. This represents the well-known direct pathway of the basal ganglia. Secondly, the cortical excitatory inputs to the striatum leads to an increase in the inhibition to the GPe, which in turn directly disinhibits the GPi/SNr, or indirectly by first disinhibiting the STN which itself facilitates the GPi/SNr. Thus, following this dishinibition of the GPi/SNR, the inhibitory influence of the GPi/SNr to the thalamus is increased, and the cortical motor neurons coding for unwanted movement are finally inhibited. This represents the well-known direct pathway of the basal ganglia. The direct and indirect pathways of the basal ganglia have been also called the Go and NoGo pathways, respectively (*e.g.*, see Frank, 2000), and thus allow facilitating and suppressing wanted and unwanted movement, respectively. Of note, the loop described here is an open one[48], but closed cortico-striato-thalamo-cortical loops are also involved in parallel during focused motor attention. In this case, the cortical excitatory input to the striatum originates from the motor cortices.

Finally, the role of the SNc, which has not been addressed in this subsection so far, may be considered as quite different from the role of the other structures constituting the cortico-striato-thalamo-cortical circuitry. As I above-mentioned, the SNc bound to the

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[48] This cortico-striato-thalamo-cortical loop is considered as an open one as its inputs originate from the fronto-parietal network while the output cortical structures are the motor areas.

striatum through both excitatory and inhibitory projections, and this represents the only neural structure of this network possessing this double function. The "double function" of the SNc is actually allowed because this structure is comprised of dopaminergic (DA) neurons, DA being a neuromodulator - not a simple neurotransmitter - which modulates excitability depending on the receptor on which it fixates. DA release in the striatum indeed allows for modulating excitatory inputs to this structure originating from the cortex and have opposing effects on the direct and indirect pathways of the basal ganglia: DA facilitates the former, and inhibits the latter. This opposing effect occurs *(i)* because the two classes of DA receptors, known as D1 and D2 receptors, are respectively expressed in neurons involved in the direct and indirect pathways (*e.g.*, see Aubert et al., 2000) and *(ii)* because DA have excitatory and inhibitory effects while fixated on D1 and D2 receptors, respectively (*e.g.*, see Hernandez-Lopez et al., 2000). Now, given that the striatum projects inhibitory inputs to SNc, during focused motor attention, the striatum neural activity being facilitated (see above), the SNc actions on the striatum are inhibited. Thus, the Go, direct pathway is facilitated but mainly by cortical inputs - the SNc excitatory input being diminished, and the NoGo indirect pathway is facilitated by cortical input and less inhibited by the SNc projections.

Overall, all these functional neural interactions constitute the basis of the selective gating mechanism (Frank et al., 2001) associated with focused motor attention. In the next subsection, I discuss the involvement of additional neural pathways in the process, before depicting through a schematic arrows-and-boxes representation the *brain network for focused motor attention* (please see Figure 1.14).

1.3.4.2. Involvement of the additional neural pathways in focused motor attention

Involvement of cortico-cortical interactions

In the above subsections, evidence has been provided regarding the involvement of a fronto-parietal network in focused motor attention. The involvement of this network has been then discussed in relation to the cortico-striato-thalamo-cortical circuitry. As regards to the focused sensory attention process, we have however seen that beyond the cortico-subcortical interactions, the fronto-parietal network also directly influences the sensory cortices' activity (*e.g.*, Miller and Buschman, 2013). In a similar manner, a number of authors have proposed a modulation of motor cortices' activity by the fronto-parietal network through direct cortico-cortical pathways (*e.g.*, Andersen and Buneo, 2002; Andersen and Cui, 2009; Cisek and Kalaska, 2010; Mars et al., 2011). As discussed by Miller and Buschman (2013), cortical-related top-down signals are excitatory in nature. Based on glutamatergic excitatory synapses, the main direct action of the fronto-parietal network would indeed result in enhancing the neural activity in motor pyramidal cells related to the movement on which attention is focused on. Then, through lateral inhibition mechanisms, the neural representation of unwanted movements can occur, such as it has been described in sensory cortices during focused sensory attention (please see p. 75). Finally, reciprocal mutual interactions are present within the secondary motor areas and between them and M1 (Brunia, 1999).

Involvement of additional thalamus-related pathways

I have just mentioned that similar cortico-cortical interactions occur in sensory and motor attention processes. It seems that a number of thalamic-related mechanisms are also involved in a similar way in both processes. For instance, Brunia (1999) described the involvement of cortico-thalamo-cortical loops involving the motor cortices. Such loops are glutamate-based and therefore involve excitatory interactions in nature. Thus, during focused motor attention, these recurrent circuits allow the maintenance of an increased level of firing rate within the motor neurons related to the to-be-executed movement. Finally, the lateral inhibition mechanisms proposed by Pinault (2004) and detailed in Figure 1.12, is likely to occur in motor attention as well (*i.e.*, as discussed by the author). In this way, focused motor attention first operates through a facilitation of the activity of the thalamic neurons projecting to motor cortical neurons related to the to-be-executed movement. Following this facilitation, a neural suppression is allowed through lateral inhibition mechanisms as described in Figure 1.12. These thalamic lateral inhibitions directly modulate the level of inhibition in motor cortices, allowing then to suppress the activity of the neural pathways related to unwanted movements.

In summary, focusing attention to a particular to-be-executed movement involves a large brain network comprised of several sub-cortical and cortical structures. The basal ganglia are at the very basis of this *brain network for focused motor attention*, which rests on the well-known cortico-striato-thalamo-cortical circuitry. In addition to the cortico-striato-thalamo-cortical circuitry, further cortico-cortical, thalamo-cortical and thalamo-thalamic neural interactions support motor attention. According to Brunia and colleagues (*e.g.*, Brunia 1993, 1999; Brunia and Van Boxtel, 2001), the source that triggers the focusing of motor attention also resides in the anterior attentional complex (*i.e.*, LPFC and ACC). *In fine*, all these neural interactions lead to the expression of motor attention within the motor cortices, characterized by a "*plus - minus*" neural signature. The *brain network for focused motor attention* is presented in Figure 1.14, hereafter.

The last subsection - titled "The Neuroscience of focused attention" - has allowed us to identify **what neural structures support focused attention**, which represents one of the identified aims of this thesis. Depending on the domain - whether sensory or motor - focused attention involves divergent neural networks but similar neural mechanisms. The sensory and motor cortices can be considered as the sites where sensory and motor attention are expressed, respectively, exhibiting antagonistic neural facilitation - inhibition mechanisms. Further, at the cortical level, the fronto-parietal network represents a key structure in both sensory and motor attention, with a very particular role of the prefrontal areas in the top-down control of the process.

Reminder Box IV

Focused sensory and motor attention processes are expressed in the same way in sensory and motor cortices, respectively.

Yet, two different and broad brain networks support the sensory and the motor attention processes.

The brain network for focused sensory attention involves the LC in the brainstem, the basal forebrain, the thalamus and fronto-parietal cortical areas .

The brain network for focused motor attention involves the basal ganglia, the thalamus and fronto-parietal cortical areas.

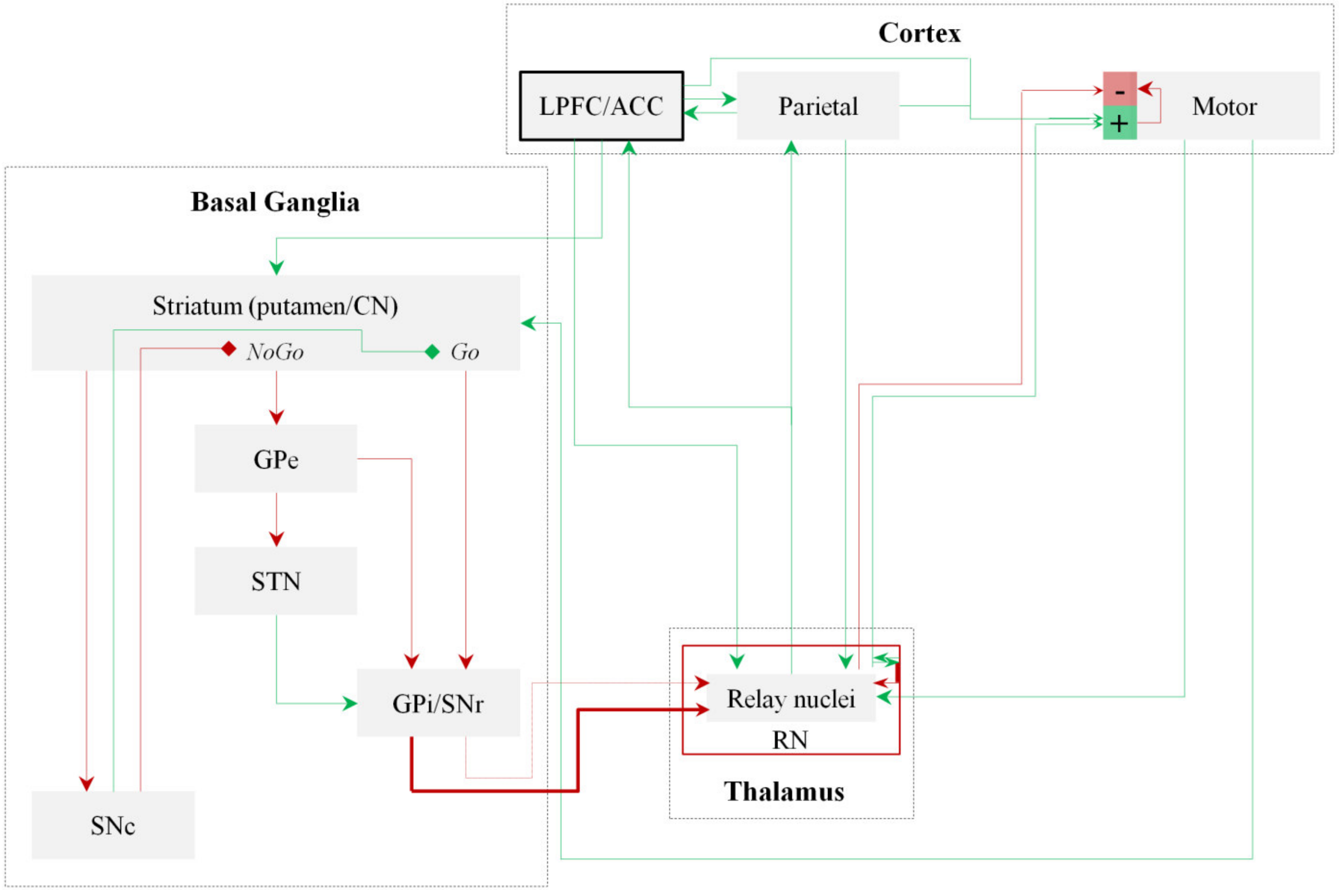

Figure 1.14: Schematic arrows-and-boxes representation of the brain network for focused motor attention. LPFC: lateral prefrontal cortices; CN: caudate nucleus; GPe: globus pallidus - external segment; GPi: globus pallidus - internal segment; STN: sub-thalamic nucleus; SNr: substantia nigra pars reticulata; SNc: substantia nigra pars compacta; RN: reticular nuclus. Green and red arrows represent excitatory and inhibitory neural activity, respectively. Likewise, the green "+" and red "-" boxes represented within the motor cortices, depict the facilitation occurring in neurons related to the to-be-executed movement and the inhibition occurring in neurons related to unwanted movements. Given the critical role of the basal ganglia in this network, a focus has been made on these structures. The square-ended arrows originating from the SNc represents the modulatory role of DA on the *Go* and *NoGo* pathways, according to the terminology exploited by Frank (2000). The bold and the dotted arrows bounding from the GPi/SNr to the thalamic relay nuclei represent the increase and decrease in inhibition in the NoGo and Go pathways, respectively. The lateral PFC/ACC complex is taken as the origin of the engagement of this network.

"*What is attention?*", was the issue and the title of this section, which concludes here. The last sixty pages bear witness to the fact that the question was really worth asking. The last 22,000 words demonstrate how much the issue has long since fascinated scientists, and how arduous it still remains to answer. Nonetheless, we have pointed out some key ideas throughout this section. One of these key ideas is that, as I evoked at the very beginning of this thesis (see p. 21), focused attention plays a crucial role in both humans' perceptions and actions. That, however, does not indicate what attention is. But that, nonetheless, led us to interesting observations: both sensory and motor attention involve two main mechanisms, which suggests that these mechanisms may actually constitute the very essence of attention. Focused attention involves the enhancement of a given target - whether a particular movement to execute or a particular sensory stimulus to process - concomitant with the suppression of all other potential targets - whether unwanted actions or irrelevant sensory materials. One may thus define what attention is by defining how it works: "*Attention is plus with a minus!*". Attention is a cognitive function, and thus, the most relevant way to define what it is, is to define how it functions.

The vital cognitive function that represents attention is however, a process that entails some deficiencies. Some pages ago, I put forward the idea that attention can be focused with different levels of intensity at a given time, as divided attention theories put forward in the 1980s through the limited resources theory of attention (please see pp. 41-48). Over time as well, attention fluctuates. Even healthy people are unable to maintain focused attention over time. The next section addresses this issue.

2. On the inability of humans to sustain attention

The literature overflows with papers detailing examples of the manifestation of attention decrement in daily life (*e.g.*, Langner and Eickhoff, 2012; or, for a remarkable example of attention decrement in an elite soccer player, see the introduction section of Manly et al., 1999). In a famous lecture note in 2003, Ian Robertson notably reported catastrophic facts regarding two traffic accidents. The first related to a train driver who missed critical signals[49] and provoked a disastrous train crash. The second was about a car driver who was sleep-deprived and had driven for hours, before plunging from the motorway down onto a railway. A few seconds later, a train passed on that railway and derailed. These tragic accidents caused the death of several people. Such examples basically catch readers' attention. Such examples force readers, including me, to keep reading the paper, attentively. Such examples ultimately demonstrate how crucial it is for humans to better understand the attention decrement phenomenon.

Yet, the neural correlates of attention decrement have not been much explored so far (Langner and Eickhoff, 2012). In fact, when the field of modern neuroscience exploded in the late 1980s (see p. 51), most of the efforts made by researchers were first dedicated to the investigation of attention under conditions of full capacity. As we have seen in the previous section, these investigations have crucially impacted our current knowledge of attention. They have allowed us to identify *what* neural structures support sensory and motor attention, and to further define how attention functions. In a similar manner, investigating the neural correlates of attention decrement represents a stepping stone in our understanding of the phenomenon. This section reports what we currently know about attention decrement, an account which is primarily based on behavioral markers and related theoretical accounts. I also develop a qualitative review of the (too) few studies which have investigated the neural correlates of attention decrement. Accordingly, I discuss how the findings from these early neuroscience studies discredit certain theoretical accounts, while reinforcing others, providing evidence of the very importance of neuroscience in understanding the phenomenon. Based on both the behavioral and neural findings from the literature, I end the section by stating the current issues and the objectives of the first part of the present thesis (*i.e.*, PART I - COGNITIVE NEUROSCIENCE).

2.1. What sustained attention, vigilance, and vigilant attention are, and what they are not

A certain ambiguity has for a long time resided in the attention literature regarding the definition of sustained attention, vigilance, or even arousal, terms which have indeed been

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[49] Or, as Robertson (2003) argued later in his paper, attention decrement in this train driver could have elicited **an incapacity to withhold the given motor action, that is, driving forward**.

often used interchangeably (*i.e.*, as discussed by Robertson and Garavan, 2004). Before describing the behavioral markers of attention decrement, there is a need for determining which tasks are exploited to experimentally elicit such decrements, and which specific attention abilities are associated with each task.

In Figure 1.5, page 49, I defined the different components and sub-components of attention according to the typographies given by Posner and Rafal (1987) and by VanZomeren and Brouwer (1994). In this representation, I grouped together *vigilance* and *sustained attention* within a single sub-component of attention. This suggests that both psychological concepts involve similar characteristics that are at least distinguishable from the other intensity-related sub-component, that is, *phasic alertness*. Vigilance and sustained attention do share characteristics, but are however not identically investigated, and defined (*e.g.*, Oken et al., 2006; Robertson and Garavan, 2004; Robertson and O'Connell, 2010; Sturm and Willmes, 2001).

The concept of **vigilance** in psychology appeared with the work of Mackworth, in 1948, on radar operators. Vigilance[50] was then defined as the function needed by radar operators in order to detect rarely occurring events - signaling the presence of enemies - on screens displaying large number of friendly events over prolonged periods of time (*i.e.*, often more than an hour). In this sense, vigilance tasks basically involve the detection of rare targets among a flow of distracters. For instance, in the Mackworth's clock test, participants have to visually focus on a screen that displays a small dot moving around the circumference of a clock by making small jump. Occasionally, the jump of the dot is larger and participants have to respond by pressing a button to signal that they have detected the target event. The task duration in the initial version of the Mackworth's clock test is of two hours. Another largely exploited task is the continuous performance task (CPT) developed by Rosvold et al. (1956), in which subjects have to detect rarely occurring target stimuli - letters or numbers - among a flow of other letters or numbers.

Sustained attention, meanwhile, involves the capacity to accurately respond to frequently occurring sensory events over a prolonged period of time (Robertson and O'Connell, 2010). In this sense, the typical task exploited to assess sustained attention abilities

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[50] I refer here to the use of the term *vigilance* in cognitive psychology. As relevantly pointed out by Oken et al. (2006), the term vigilance possesses other definitions, most noticeably in clinical neurophysiology where vigilance is related to changes in sleep-wake states.

is the psychomotor vigilance[51] task (PVT) developed by Dinges et al. (1997). In this task, participants have to respond as fast as possible to targets occurring with random ISIs ranging between 2 and 10 sec. In the PVT, no distracters are presented to the subjects. However, sustained attention can also be assessed with a low number of distracter stimuli, requiring the subject to withhold the motor response.

This is especially the case in a sustained attention to response task (SART), developed by Robertson et al. (1997). In a version of this task, participants are required to press a key in response to the numbers 1, 2, 4, 5, 6, 7, 8, 9 but not to the number 3. The numbers appear at unpredictable moments in time[52]. **Vigilant attention** was the term suggested by Robertson and Garavan (2004) to refer to the kind of ability required in this task. The main aim of Robertson et al. (1997) was to propose a task reproducing the occurrence of action slips, in highly automated, routine action sequences. Compared to long-duration vigilance tasks, the authors demonstrated that the SART was sensitive to momentary lapses in attention, occurring after only a few minutes of vigilant attention, even in healthy subjects. A similar task has been proposed by Conners (2000) as an adaptation of the CPT and is known as the Conners' CPT.

Further, defining what a function is - here sustained attention - may also involve defining what it is not. It appears important to determine what arousal is, and what differences exist between arousal and sustained attention - arousal and sustained attention having been used interchangeably in the literature (Langner and Eickhoff, 2012). According Oken et al. (2006), arousal "*refers to non-specific activation of cerebral cortex in relation to sleep–wake states*". In this sense, arousal may be considered as really closed to the definition given to vigilance in clinical neurophysiology.

Overall, vigilance, sustained attention and vigilant attention represent separate aspects of humans' ability to maintain attention over time that are engaged in different types of tasks. The main behavioral variables extracted from these tasks consist of *(i)* the number of omission errors (*i.e.*, of missed targets), *(ii)* the number of commission errors (*i.e.*, also called false alarms (FA) corresponding to motor responses given while NoGo target or no target appears) and *(iii)* the RT. It is worth highlighting that each type of task is sensitive to different behavioral variables. For instance, the most sensitive marker of the level of vigilance is the

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[51] Ironically, one of the main tasks exploited to assess sustained attention is named *vigilance task*.

[52] A version of the task with fixed ISI, called $\mathrm{SART}_{\mathrm{fixed}}$ - as opposed to the $\mathrm{SART}_{\mathrm{random}}$ - has been developed as well (Manly et al., 2003). The two versions have been shown to engage different executive functions (*e.g.*, see O'Connell et al., 2009).

number of omissions while the most sensitive marker of the level of vigilant attention task is the number of commissions. Also, in order to provide a full picture of the sensory and motor deficiencies associated with attention decrement, I will base my argument on each of the three above-mentioned types of paradigm.

2.2. What is attention decrement? How and why does it occur?

Having defined what focused attention and sustained attention are, the issue is now to better determine what attention decrement is. Firstly, behavioral manifestations of the phenomenon are key elements to answer. As above-mentioned, the literature provides a number of examples of the manifestation of attention decrement in humans' daily life. Philip et al. (1999) reported an increase in RT over TOT in healthy drivers. Robertson (2003) reported the incapacity of a train driver to withhold routine action sequences which led that driver to keep driving forward in spite of the occurrence of imperative signals. World War II radar operators showed decreases in perceptual sensitivity to rarely occurring critical signals while the features of these signals did not change over time. Thus, as described early in the introduction section of this thesis, attention decrement manifests through three main behavioral signatures, that is: increases in RT and in motor impulsivity and decreases in perceptual sensitivity. Secondly, understanding the causes of such sensory-motor deficiencies in the context of attention decrements has involved theoretical discussion in the literature. In this vein, two main theoretical accounts have been advanced: the resources theory and the mindlessness theory. I discuss these two theories hereafter. Finally, I end the current subsection by proposing additional explanation relating the potential neural mechanisms underlying the attention decrement phenomenon.

2.2.1. Resources theory of attention decrement

Resources theorists of attention decrement commonly argue that the need for sustaining attention fatally leads to a depletion of information-processing "resources" which are not replenished fast enough as time elapses (*e.g.*, see Parasuraman et al., 1987; Nelson et al., 2013; Shaw et al., 2013; Warm et al., 2008). To me, this attempt for an explanation of how and why attention decrements occur during sustained attention tasks results from a direct and dangerous transfer of the resources theory from the divided attention literature. The resources theory has been indeed initially launched by Kahneman (1973, see p. 41) and contemporary cognitive psychologists (*e.g.*, Norman and Brobrow, 1975) in order to explain the degradation in behavioral performance observed in humans performing two, or more, attention-related tasks simultaneously. Later on, their proposition of a limited resources theory of divided attention has been supported by neurophysiological findings (Scalf et al., 2013), which I describe hereafter. Thus, the main pillar of the resources theory in the context of attention decrement is actually its validity in the divided attention literature. However, as we will see in this subsection, the neurophysiological basis of the definition of resources in the divided attention literature is not the same as that of resources in the attention decrement literature, where resources are often modeled as a “fuel” or a “juice” in the brain (Mozer and Sitton, 1998). The main problem that I have encountered when I have tried to address the issue of attention decrement through a resources-based theory is that I simply did not find any compelling and concrete evidence of what these so-called "resources" are. Do the limited level of resources represent a limited amount of glucose, of oxygen, of lactate, of a certain neurotransmitter, or neuromodulator, or even of sodium and potassium in the neurons' membranes? To the best of my knowledge, there is currently no answer to this question in the attention decrement literature. Further, resources theorists of attention decrement have commonly based their argument on two other pillars. The first considers behavioral "evidence" in favor of a resources theory of attention decrement, while the second is based on indirect neurophysiological measurement-derived assumptions. In the present subsection, I first describe why the resources theory of divided attention can be currently considered as valid, based on the underlying neural mechanisms. I then present the main behavioral and neurophysiological "evidence" on which resources theorists of attention decrement have based their interpretation until now. I discuss their relevance and propose alternative explanation of these findings.

2.2.1.1. Resources theory: validity in the context of divided attention

As described in page 41, the initial idea that Kanheman developed in his book in 1973 (page 16), was the following: "*Interference between tasks is due to the insufficient response of the system to demands, and to the narrowing of attention when effort is high*". To what resources theorists of attention decrement extrapolated (Nelson et al., 2013): "*The resource theory assumes that cognitive processing relies on a limited pool of resources that, **once depleted**, lead to performance decrements (Kahneman, 1973; [...])*". While neural-based explanations of the resources theory of divided attention have been compellingly described in the literature (*e.g.*, for a recent review, please see Scalf et al., 2013), there is currently no concrete neurophysiological evidence of such a depletion of "resources", or a lack of replenishment of these resources over time. Hereafter, I briefly report the neurophysiological evidence in favor of a resources theory of divided attention.

In fact, the amalgam that seems to have emerged with the transfer of the resources theory as an explanation of attention decrement probably originates from the terminology that exploited Kahneman (1973) who assimilated the processing/attentional resources as a "*power supply*". This has been rectified later on, for instance by Bundesen et al. (1998, 2005) and Palmer et al. (2000), who defined in their computational models of visual attention the neurons as being the information processing resources - a view fully in accordance with the multiple pools of resources developed by Wickens in the 1980s (*e.g.*, Wickens, 1984). In this vein, a pool of neurons represents actually a pool of resources, and not any kind of unidentified and abstract "fuel" or "juice" (Mozer and Sitton, 1998), or even "gas" (Salf et al., 2013), according to the terms of the resources theorists of attention decrement. Scalf et al. (2013) provided then a plausible explanation of the limited resources in divided attention, considering the neural cells as being these so-called information-processing resources. Actually, the authors argued, one may *not* consider the number of neurons as the origin of the limited information processing resources. Rather, according to a widespread literature, the limitation in humans' information processing is related to the occurrence of mutual inhibitory interactions between neural cells during divided attention tasks, inhibitory processes that are at the very basis of a ***competition for representation*** mechanism (Desimone and Duncan, 1995; Duncan, 1995, 1998; Duncan et al., 1997; Kastner and Ungerleider, 2000). Visuo-spatial attention investigation have well described this mechanism. One compelling example of the *competition for representation* mechanism comes from single-cell recordings in monkeys. Reynolds et al. (1999) reported V4 neurons' responses to two stimuli presented simultaneously within its RF were inferior to their responses to each individual stimulus presented alone. Similar findings have been later demonstrated for several visual cortical areas in humans using fMRI (*e.g.*, Kastner et al., 1998, 2001; Beck and Kastner, 2005, 2007). Further, attending to multiple stimuli produces exactly the same competing interactions as these observed in such "passive perception" conditions (Scalf and Beck, 2010; Scalf et al., 2011). Such neural signatures are actually not surprising if one consider the involvement of lateral inhibitory interactions in focused attention (and actually in perception in general). Roughly, divided attention can be thus considered as a simultaneous realization of two (or multiple) focused attention tasks[53]. Focusing attention on two visual stimuli would involve mutual lateral inhibitory interactions in pools of neurons responsible for processing these stimuli, giving a compelling explanation of the decrement of performance observed during divided attention tasks. This provides explanations for the observations of Wickens (1984), that is, that tasks performed simultaneously interfere at the behavioral level only if they share similar characteristics. Indeed, realizing two auditory tasks simultaneously would involve pools of auditory neurons that are thus more likely to mutually inhibit themselves than if the tasks would involve performing a visual and an auditory tasks simultaneously.

Thus, **at any given time**, the level of "processing" resources, that is, **the level of activity in pools of neurons**, **is limited**. According to such an interpretation, the processing resources do not represent any kind of substrates conveying energy to brain structures in order to perform attentional tasks, as resources theorists of attention decrement assumed - either implicitly or explicitly. Epistemologists like Thomas Kuhn[54] (1962) have deeply studied the phenomenon of transfer of theories in Science, whose has systematically led to conceptual mistakes in the History of Sciences. Such phenomenon can be due, according to Thomas Kuhn, to the Scientist training, who learns at very early stage in his training to settle data in conceptual "boxes". Data that does not fit with the Scientist theory are either rejected or made more compliant with the basic assumptions of the theory. Further, Thomas Kuhn argued, interpreting scientific data according to a given theory should require the Scientist to re-consider the initial works that are at the very basis of the given theory. Such a reconsideration may prevent conceptual mistakes. Now that we have reconsidered the initial work at the very basis of the resources theory of divided attention, we can discuss why attention decrement could not be explained based on resources theory according to currently existing findings. I accordingly propose alternative explanation of the data obtained by resources theorists of attention decrement.

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[53] I voluntarily simplify the definition of divided attention in order to gain clarity in the explanation given. However, the neural mechanisms underlying divided attention-related have been demonstrated as not being a simple addition of the neural mechanisms underlying focused attention, but also involves additional cognitive function, related for instance to higher need for executive control (Nebel et al., 2005).

[54] Earlier, Ludwig Fleck (1935) actually raised the same conclusions as Kuhn in his book titled *Genesis and Development of a Scientific Fact*.

2.2.1.2. Behavioral "evidence" for a resources theory of attention decrement

Thus, according to resources theorists of attention decrement, processing resources are a kind of juice, of gas, of fuel or, in other words, a supply that is depleted over TOT but not replenished in the available time, leading to the observed sensory-motor deficiencies. In order to demonstrate the validity of this assumption at the behavioral level, the main idea of resources theorists has been to develop sustained attention tasks with different levels of difficulty. The hypothesis was then that the higher the level of task difficulty, the faster the depletion of resources and the stronger the behavioral deficiencies with TOT. This hypothesis was validated, as described below. But other potential explanations of these findings can be offered.

Several studies have indeed described an amplification of the behavioral performance deficiencies with attention decrement when task difficulty was increased (*e.g.*, Caggiano and Parasuraman, 2004: Helton and Russel, 2011; Smit et al., 2004; See et al., 1995; see Warm et al., 2008, for review). I report here two representative examples from this branch of the literature and one other study to which I contributed (Mandrick et al., 2013b[55]) which has sought to describe the relationship between task difficulty and behavioral performance decrement during sustained attention tasks. Smit et al. (2004) asked subjects to perform a CPT-like task of 40-min duration with four levels of difficulty. The authors reported that behavioral performance deterioration did not occur for the two lowest levels of difficulty but did occur for the two highest levels of difficulty. They accordingly concluded that increasing the level of task difficulty increased the attentional demand which led to a higher depletion of "resources". Other examples of the effect of task difficulty on attention decrement come from dual-task studies. For instance, Helton and Russel (2011) asked seven hundred and forty five participants to realize a target detection task while performing simultaneously other tasks either involving or not involving working memory load. The dual-task lasted 10 minutes for each condition. This time, in all conditions, the task induced an increase in RT and a decrease in perceptual sensitivity over time, illustrating the attention decrement occurrence. However, the behavioral deficiencies were exacerbated in the working memory load condition. Again, the interpretation was that "hard work" requires more processing resources, not replenished in the available time. In the above-mentioned study to which I contributed (Mandrick et al.,

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[55] Mandrick K, Derosiere G, Dray G, Coulon D, Micallef JP, Perrey S. (2013b). Utilizing Slope Method as An Alternative Data Analysis for Functional Near-infrared Spectroscopy-derived Cerebral Hemodynamic Responses. *International Journal of Industrial Ergonomics*, 43:335-341.

2013b), three levels of task difficulty were investigated during an arithmetic task of 60-sec duration. For each level of difficulty, three repetitions (*i.e.*, each of 60-sec duration) were realized with 90-sec of rest between each repetition. Prior and directly after the three repetitions four auditory simple RT were performed to test the effect of task difficulty on focused attention. Random ISI, ranging from 10 to 30 sec, were exploited. This experimental protocol allowed us to test the effect of task difficulty on focused attention following tasks that did not require a continuous sustaining of attention over time. We demonstrated that RT significantly increased following the execution of the highest level of task difficulty only. Here, a resource theorist of attention decrement would argue, with hardness, that the depletion of the "fuel" occurs very early and the replenishment of this "juice" is not fast enough to satisfy the demand even in short-duration attention tasks (*i.e.*, of 60-sec duration in Mandrick et al., 2013b). I provide a more plausible explanation of these results next.

Several fields in psychology have described the phenomenon observed in the three different studies described above. In these fields, investigation has for instance been conducted on the negative and positive effects of the level of anxiety, stress or even punishment on memory, learning and decision-making among other cognitive functions (Teigen, 1994). The common observation is that excessively high or low levels of stress or anxiety dramatically lead to an overall decrease in behavioral performance. Behavioral performance is however at its maximal level if humans (and even animals) are in a medium, optimal level of stress. A psychology law is at the very basis of these observations: the Yerkes-Dodson law (1908), describing the inverted-U-shape function between the level of stress and the level of behavioral performance (*e.g.*, Salehi et al., 2010). This phenomenon is well accepted in the psychology literature and possesses well-identified neurobiological basis (*e.g.*, please see Calabrese, 2008, for review). In accordance with this law, in Mandrick et al. (2013b), we measured significantly higher scores of NASA-task load index following the realization of the highest level of task difficulty as compared to other levels of difficulty. Increasing the level of task difficulty is thus more likely to increase the level of stress and anxiety which directly impact on behavioral performance. Thus, the amplification of the performance degradation with TOT observed while increasing the level of task difficulty could actually result from a higher level of stress in such conditions. Finally, sustaining attention has been shown to be associated with high levels of stress (Warm et al., 2008) and further increasing the level of stress due to an increase in task difficulty could have an additive or even multiplicative negative effect on behavioral performance.

2.2.1.3. Neurophysiological "evidence" for a resources theory of attention decrement

The main neurophysiological "evidence" for a resources theory of attention decrement comes from *(i)* recent transcranial direct current stimulation (tDCS) investigation; from *(ii)* cerebral blood flow velocity (CBFv) measurements, usually performed using transcranial doppler sonography (TCDS); and from *(iii)* disparate neuroimaging studies using NIRS, PET or fMRI. Overall, all these studies, even the tDCS ones (please see below), exploited hemodynamic-related measurement of brain activity. The reason is that hemodynamic variables are supposed to reflect the level of supply conveyed to brain structures and thus the level of resources, even if these resources are not explicitly defined. The validity of these three types of studies in support of the resources theory of attention decrement is discussed next.

tDCS is a non-invasive technique that allows for modifying cortical neurons' membranes excitability by applying a low current (1 to 2 mA) through electrodes positioned at the surface of the scalp. Recently, Nelson et al. (2013) applied tDCS on the right and left LPFC in different conditions during a 40-min duration CPT. I will focus on one condition in which anodal tDCS[56], known for increasing the level of cortical excitability, was applied over the right LPFC during the first 10 min of the task. CBFv was concurrently measured in the left and right middle cerebral artery by means of TCDS. The NIRS-measured cortical activation was also recorded over the right and left LPFC. The authors found an increase in RT and a decrease in perceptual sensitivity during the CPT in the sham condition, while these attention decrement behavioral signatures were reduced in the anodal tDCS condition. They interpreted these results in a resources theoretical framework, and considered that anodal tDCS increased the level of resources, allowing thus to perform better on the sustained attention task. One other result was that the TCDS-measured CBFv decreased with TOT and that this decrease was reduced in the anodal tDCS condition. However, strikingly, the last result was that the NIRS-measured cortical activation did not decrease during the task. LPFC activation actually slightly increased with TOT in the sham condition and further increased over time in anodal tDCS condition. There are three main points to consider here which clearly show the weaknesses of the resources theory of attention decrement at the neurophysiological level. First of all, the fact that anodal tDCS reduces performance decrement and increases hemodynamic activity does not necessarily reflect that resources

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[56] Other experimental conditions included cathodal stimulation and *late* stimulation, that is, stimulation applied after 30 min of task.

were limited before the tDCS treatment. That boosting the neurons' activity by tDCS increases cortical hemodynamics and reduces the decrease in CBFv demonstrates that these hypothetical "resources" are actually not limited but still available. **tDCS does not play the role of accelerating the process of replenishing the hypothetical resources**. Secondly, if one considers processing resources as a supply provided by the systemic circulation, the increase in NIRS-measured cortical activity in the left and right LPFC with TOT totally supports the inference that resources are actually increasingly conveyed to this brain area throughout the task. Yet, behavioral deficiencies occurred. Thus, this result clearly counters the resources theory of attention decrement. Finally, this finding also highlights that the relationship between *(i)* cortical activation as measured by neuroimaging techniques such as NIRS and *(ii)* CBFv as measured during TCDS is not a linear one. In this study, there is a clear decoupling between measurement of CBFv at the middle cerebral artery and NIRS-measured cortical activation. Still, the most developed argument of resources theorists of attention decrement is based on the TCDS-measured decreases in CBFv with TOT. Such decreases are actually not the manifestation of an overall decrease in cerebral activity.

Results from a particular study investigating the decrease in CBFv with TOT are of interest to my arguments (Mayleben, 1998). This study demonstrates the problem in considering TCDS-measured CBFv a marker of an hypothetical depletion of resources with TOT. Mayleben (1998) showed that performing a vigilance task involving working memory amplified the performance decrement compared to performance measured without the working memory component, a behavioral result that can be explained based on the Yerkes-Dodson law. According to the resources theory however, this amplification of the behavioral deficiencies with the increase in task difficulty is related a higher demand for processing resources leading to a faster depletion. The author also described the evolution of the CBFv for each condition and proceeds to test two hypotheses: *(i)* that CBFv reflects changes in the level of "resources"; *(ii)* that "resources" decreased faster in the working memory load condition. Briefly, Mayleben (1998) found a decrease in CBFv in both conditions and an overall higher CBFv in the working memory condition. The point is, that the slopes of these decreases in CBFv were the same in both conditions. Contrariwise, the resources theory of attention decrement would have predicted that the decrease in CBFv is faster in the working memory condition, because of the higher demand of the task. Thus, Mayleben (1998) demonstrated a stronger behavioral performance decrement with increasing task difficulty, but not related to a stronger decrement in what resources theorists consider as a signature of processing resources consumption, that is, CBFv.

On that account, one may assume that macroscopic measurements of brain hemodynamic activity (*i.e.*, TCDS) do not support the resources theory of attention decrement. So, what about neuroimaging measurements which, meanwhile, more specifically reflect changes in regional, local brain structures' activity? As Langner and Eickhoff (2012) pointed out, a very limited number of studies have investigated the changes in brain activity associated with attention decrement to date. Among these few studies, Paus et al. (1997) and Coull et al. (1998) are often cited by resources theorists of attention decrement (*e.g.*, Shaw et al., 2013) as they described TOT-related PET- and fMRI-measured deactivations, respectively, in a number of brain structures. What the resources theorists commonly omit to mention is that these two studies also reported increased activity in a number of attention-related areas with TOT[57]. And these two studies are not isolated in their findings. For instance, the previously mentioned results from Nelson et al. (2013) provide similar evidence: the activity of some brain structures increases with TOT while behavioral performance decreases. In the same vein, Butti et al. (2006a) showed an increase in the NIRS-measured right PFC activity throughout a 10-min duration Conners' CPT while, according to the author, the subjects produced an increase in behavioral "errors" with TOT (*i.e.*, the authors potentially referred to an increase in the number of omissions and commissions). They replicated these results using fMRI (Butti et al., 2006b) and demonstrated that the right PFC was not isolated in its increased activity with TOT. An increased activity was indeed also demonstrated in several cortical areas including left LPFC, right parietal areas and SMA. Yarkoni et al. (2009) studied the trial-by-trial relationship between fMRI-measured brain activity and RT. RT increases observed as an effect of TOT was linearly correlated with the level of activity of the bilateral PFC. A similar finding was found by Weissman et al. (2006) who in addition demonstrated an increase in parietal and in the M1 area involved in the motor response following lapses in attention. Drummond et al. (2005) compared the behavioral performance and fMRI-measured brain activity of subjects who have had *(i)* a normal night of sleep (control group) or *(ii)* 36 hours of total sleep deprivation (TSD group). In the control group, the slowest RTs (*i.e.*, mostly occurring at the end of the PVT) were associated with increased activities in bilateral PFC, right parietal areas, and basal ganglia. Furthermore, the behavioral

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[57] The title of the study by Coull et al. (1998) was even "*Monitoring for target objects:* ***activation of right frontal and parietal cortices with increasing time on task***".

performance of the TSD group was significantly lower than that of the control group and this was associated with further increases in the activity of these identified brain regions. Finally, in the previously mentioned study by Mandrick et al. (2013b), the right and left LPFC activities were also investigated by NIRS while participants performed tasks with different levels of difficulty. In brief, we found a significant increase in both LPFC activities with increasing task difficulty (Figure 1.15). The "*blood supply*", as measured by NIRS, was higher in the highest level of task difficulty (please see Figure 1.15, below). Yet, the attention-related RT task performed just after the highest level of task difficulty showed decrement in behavioral performance. Thus, behavioral performance can deteriorate even in the presence of "resources", again if one considers the circulation as conveying these undefined resources.

In summary, it seems that the activity of a number of cortical and sub-cortical brain structures increase with TOT, most of them being attention-related areas. Such findings definitively discredit the resources theory of attention decrement. The global decrease in TCDS-measured CBFv commonly observed by the resources theorists of attention decrement appears not to be coupled with the regional changes in brain activity. Other studies have demonstrated such a decoupling between the fMRI-measured BOLD signal and the global CBF variations (Obata et al., 2004), between the CBFv and the PET-measured regional brain activity (Prielipp et al., 2001) and between CBFv and EEG desynchronization (Hajak et al., 1994, 1996; Klingelhofer et al., 1992). In fact, as previously mentioned, neuroimaging investigation of attention decrement have also reported decreases in activity over several brain structures - concomitantly to increases in activity in other brain structures (Coull et al., 1988; Paus et al., 1997), and it is more likely that a macroscopic indicator of brain hemodynamic such as reflected by CBFv fails to reveal these subtle local activation and deactivation brain patterns occurring with TOT. The occurrence of these patterns of activation and deactivation are further discussed in page 110. As a temporary conclusion, one may nevertheless consider that the brain correlates of attention decrement involves complex - antagonistic - patterns of neural activity rather than a simple overall disengagement, reducing brain activity.

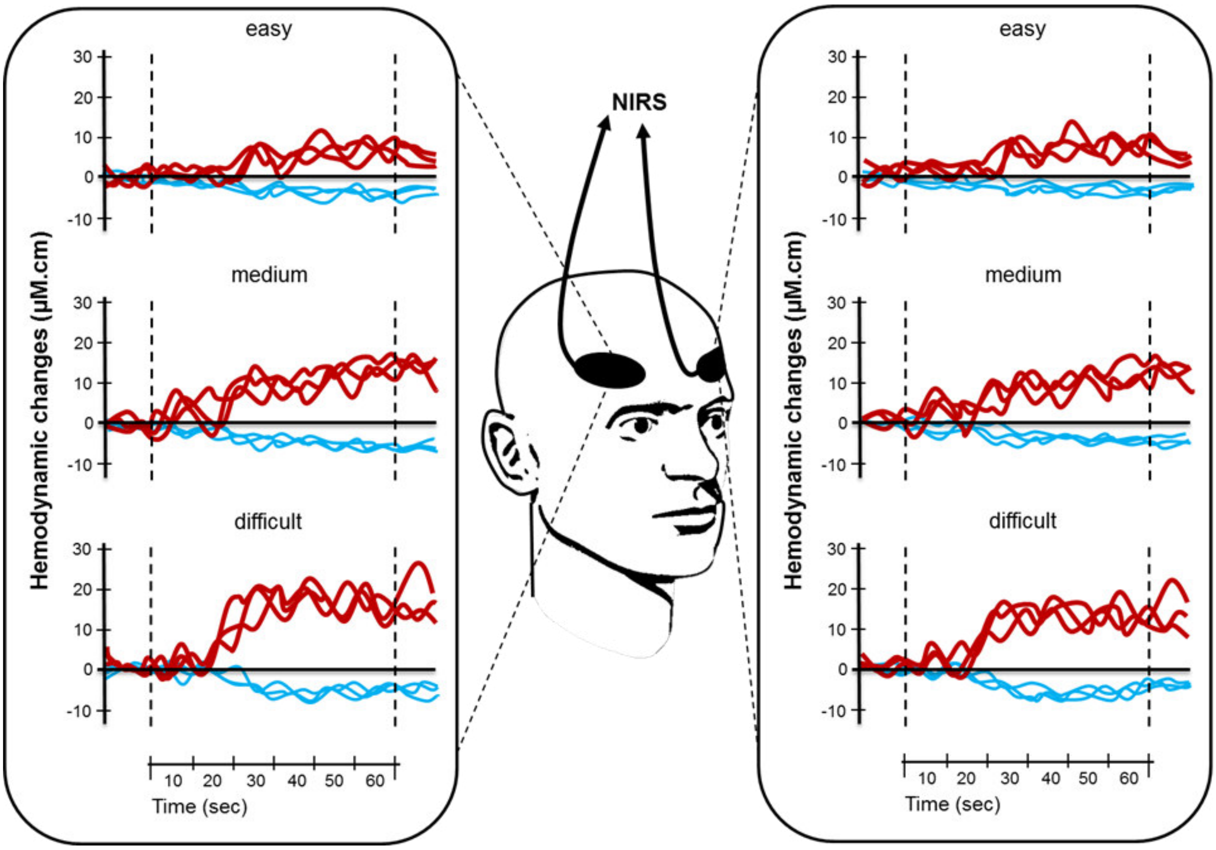

Figure 1.15: NIRS responses of the bilateral PFC areas obtained for a single subject performing a 60-sec duration MA task at three levels of task difficulty. For each level of task difficulty and each hemisphere, three repetitions have been computed. The both LPFC areas show a typical NIRS signature exhibiting an increase in O_2Hb (in red) and a slight decrease in deoxyhemoglobin (HHb, in blue). This typical NIRS signature characterizes an increase in neural activity (Hirth et al., 1996; Obrig et al., 2000). Further, the illustration clearly shows that NIRS-measured cortical activation was at highest at the end of the highest level of task difficulty for both LPFC areas. However, this was at this precise moment that the simple RT task was performed, showing that behavioral performance can decrease with high level of neural activity, at least in these attention-related cortical areas. For further information, please see Mandrick et al. (2013b).

2.2.2. The mindlessness theory of attention decrement

The mindlessness theory of attention decrement can be seen as the formal opposite of the resources theory. While the resources theory posits that sustained attention tasks lead to an "over-load" and thus to the depletion of "processing resources" in the brain, the mindlessness theory assumes that behavioral performance degradation with TOT is the consequence of a type of “under-loading” induced by the monotonous and repetitive characteristics of the task (Manly et al., 1999). According to the mindlessness theorists of attention decrement, the under-load associated with sustained attention tasks leads to a progressive disengagement from the task over time, and to a shift of attention towards self-centered matters (Braboszcz and Delorme, 2011), characterizing the so-called mindwandering episodes (Smallwood et al., 2004). Two main categories of approaches have been exploited in the literature to investigate the occurrence of such task-unrelated-thoughts (TUT) during attention tasks: *(i)* the first requires that the subjects engaged in the attention task self-report, based on introspection, whenever they experience a TUT by a button press (*e.g.*, Antrobus, 1968; Braboszcz and Delorme, 2011); *(ii)* the second is known as the *thought probe technique* (Smallwood et al., 2004), and in this approach, individuals are questioned about their state of TUT at different time points during the task and their answers are recorded either through a button press (*e.g.*, Giambra, 1995) or by a verbal report (*e.g.*, Smallwood et al., 2003). Overall, using such approaches, a number of studies have reported increases in mindwandering - or zoning out (Schooler, 2002) - episodes over TOT during sustained attention tasks (*e.g.*, Cunningham, et al., 2000; Giambra, 1995). Several interesting hypotheses have been established as to explain how and why the mind wanders, or, in other words, what are the very functions of such escape of the mind from the sensory-motor content of the currently realized tasks (for a recent review please see, Smallwood, 2013). One interesting interpretation provided by Robertson and O'Connell (2010) pertains to evolutionary neuroscience and puts forward that humans' periodic disengagements from sustained attention tasks would have presented survival advantages during evolution by preventing them from becoming vulnerable to predators. Clearly, the occurrence of such mindwandering episodes is undeniable, and is even considered as a strongly important component of human cognition (Smallwood, 2013). Smallwood and Schooler (2006) accordingly argued "*Introspective evidence is often suspect; yet, certain mental phenomena are so self-evident their existence can hardly be questioned. Our propensity for mind wandering is such a phenomenon.*"

Nonetheless, resources theorists of attention decrement do not advocate the mindlessness theory. The main argument of the resources theorists against the mindlessness theory of attention decrement is that the most simple and monotonous sustained attention tasks, that is, involving a low rate of stimulus presentation and a small number of target stimuli, are usually subjectively perceived as the most cognitively demanding (for a related discussion, please see Langner and Eickhoff, 2012). This paradoxical inverse relationship between cognitively unchallenging tasks and the required cognitive effort has long been reported by industrial psychologists who observed increased subjective effort expenditure and increased levels of stress following simple, repetitive sustained attention tasks (*e.g.*, Frankenhaeuser and Gardell, 1976). In fact, considering the increased level of stress reported following the realization of extremely repetitive sustained attention tasks, the lower behavioral performance can be again related to the Yerkes-Dodson law. In this sense, sustaining attention in tasks with very low or very high levels of difficulty[58] both lead to increased levels of stress and subjective expenditure and this can contribute, in part, to the deterioration in behavioral performance. Further, the increased number of mindwandering episodes with TOT during unchallenging tasks is not incompatible with the observation of a higher cognitive demand during such tasks: in order to re-focus attention to the content of the current sensory-motor task, humans have then to further increase the level of cognitive effort. In summary, the longer attention is sustained during cognitively unchallenging tasks, the higher the number of mindwandering episodes, the higher the need for an endogenous control, the higher the level of stress, and the stronger the attention decrement over time. None of these reported observations exclude the possibilities of the other. All these observations may even be considered concordant.

The question arises then of what are the exact neural underpinnings of attention decrement and whether they support - or at least do not discredit - the interpretations provided by the mindlessness theory of attention decrement. We have briefly previously mentioned that during sustained attention tasks the activity of a number of brain areas increases while the activity of others has been found to decrease (please see p. 106). In the next subsection, I provide an interpretation of such literature-based observations and propose additional neural explanations of the occurrence of sensory-motor deficiencies characterizing the attention decrement phenomenon.

2.2.3. Further insights into the neural correlates of attention decrement

First of all, what are the "*neural underpinnings of sustained attention*"? Answering such a question would provide us with a certain basis for defining which brain structures could potentially be involved in the attention decrement phenomenon. A recent and

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[58] By level of "*difficulty*" here, I mean the level of stimulation provided by the task. This level is either very low in monotonous, highly repetitive sustained attention tasks, or too high such as that presented in a sustained attention dual task. I argue that both types of tasks have been shown to be associated with high level of stress, contributing in part to the attention decrement.

interesting meta-analysis[59] realized by Langner and Eickhoff (2012) indicates that a strongly right-lateralized network supports sustained attention in humans. This network is comprised of cortical areas such as the mid- and ventro- LPFC, parietal areas (intraparietal sulcus, temporoparietal junction), and the anterior insula, and subcortical structures such as the thalamus and part of the basal ganglia (*i.e.*, most noticeably the putamen). In summary, the network underlying sustained attention comprised a large number of neural structures involved in sensory and motor attention as described in Figures 1.13 and 1.14, respectively. As the authors argued, the absence of convergence in the (primary) motor cortices can be due to the inconsistent use of the left or the right hand in the sustained attention RT tasks exploited in the studies included in their meta-analysis. A similar argument can be defended regarding the absence of convergence in the sensory cortices and the inconsistent use of auditory and visual stimuli in the studies included in the authors' meta-analysis.

What then are the "*neural underpinnings of attention decrement*"? This actually represents a central issue in this thesis and cannot be answered at this point of the manuscript. However, the literature provides us with some relevant findings to formulate hypotheses with regards to this question. In a study published in *Nature Neuroscience*, Weissman et al. (2006) demonstrates the complexity of the neural substrates underlying lapses in attention. The authors did not actually investigate the TOT effects on brain structures' activity but instead explored what determines the occurrence of *momentary* lapses in attention - characterized by a brief increase in RT followed by a recovery from this increase. They found that longer visual RTs were associated with a brief decrease in the neural response of the visual cortices. Also, the authors described an increase in PFC, parietal and M1 areas' activity following such brief lapses. They assumed that, just as focused sensory attention is driven by a facilitation of sensory cortices' activity, attention lapses are driven by a disengagement of the same areas. They further discussed that the increased activity in PFC, parietal and M1 was related to an attempt for recovering from such attention lapses. Similar findings and interpretations have been provided later by Drummond et al. (2005) in TSD participants (please see p. 105, for further description of the main results of this study). Overall, the results and interpretations arising from the trial-by-trial fMRI analysis performed by Weissman et al. (2006) to explain the neural correlates of *momentary* lapses in attention could be analogous in the case of attention decrement. In this vein, as identified on page 106, studies which have investigated

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[59] That a meta-analysis is made possible indicates that, as Langner and Eichoff argued, a number of studies has investigated the neural correlates of top-down sustaining of attention. However, studies having investigated the neural underpinnings of TOT-related attention decrement are actually really scarce to date.

the neural correlates of attention decrement have described increased activity in LPFC (Butti et al., 2006a, 2006b; Nelson et al., 2013; Yarkoni et al., 2009) and in parietal areas (Butti et al., 2006b; Drummond et al., 2005), thalamus (Coull et al., 1998) and basal ganglia (Coull et al., 1998; Drummond et al., 2005). Regarding the sensory cortices activity two EEG studies have pointed out a decrease in some sensory ERP components' amplitude with TOT (Boksem et al., 2005; Faber et al., 2012). Thus, one may assume that attention decrement could be underlain by a disengagement of the sensory neural structures followed by an increased activity in a number of structures underlying sustained attention. Such findings and interpretations are actually fully compatible with the mindlessness theory of attention decrement. It is reasonable to assume that, as time elapses during sustained attention tasks, there is an increased activity in attention-related brain structures in order to re-direct the increasingly wandering attention to the current task goals. According to this interpretation, the sensory cortices' disengagement are evidence of the decoupling between the sensory stimulation provided by the external environment and the endogenous attentional state[60].

All these interpretations contribute towards a better understanding of the attention decrement phenomenon. Further, the findings are actually closely related to Mackworth's first conclusion who described the attention decrement as a main result of a perceptual habituation mechanism (Mackworth, 1969[61]), which are thus consistent with the sensory cortices' disengagement. However, one may wonder why the increased activity in the top-down related areas (*e.g.*, LPFC and right parietal areas) do not allow for recovering from attention decrement or, in other words, do not succeed in counteracting its development. The two previously mentioned ERP studies (Boksem et al., 2005; Faber et al., 2012) described a decrease in sensory ERP components' amplitude throughout TOT, with no plateau or recovery from this decrease during the task. Why should sensory cortices passively disengage if attention-related areas, which in full capacities condition succeed in biasing the activity of the sensory cortices, further engage over time? Are there any complementary hypothetical explanations to the phenomenon? I propose such complementary explanations next.

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[60] One hypothesis to explain the occurrence of mindwandering episodes is that there is a decoupling between the human's endogenous control of attention and the exogenous stimulation provided by the environment (Smallwood, 2013) under certain conditions. The findings of a sensory areas' disengagement with TOT thus may be assumed as supporting the "*decoupling hypothesis*".

[61] Actually, the book of Mackworth, published in 1969, was not written by Norman Mackworth but by Jane Mackworth, his wife and research colleague. The book synthesizes however the discoveries made by their team on vigilance on the period extending from the late 1940s to the late 1960s.

2.2.3.1. Attention decrement: the hypothesis of an active inhibition of sensory cortices

Let's consider again Mackworth's (Mackworth, 1969) and contemporary researchers' (Stroh, 1971) first conclusions about attention decrement. According to these authors, radar operators' sensory-motor deficiencies result from a perceptual habituation phenomenon. So, what exactly is *habituation* in this context? Habituation can be defined as a behavioral performance decrement caused by the repetitive aspects of a specific, given stimulation (Thompson and Spencer, 1966). At the neural level, perceptual habituation has been demonstrated as involving a stimulus-specific adaptation[62] (SSA) process (Anderson et al., 2009; Farley et al., 2010; Netser et al. 2011; Malmierca et al., 2009) by which low-frequency depression leads to a decline in the efficacy of excitatory synapses in sensory neurons (Thompson and Spencer, 1966; Castellucci et al., 1970). As its name suggests, SSA represents an adaptation, more precisely a decrement in neural activity in response to an identified, given, specific stimulation when this is repeated over time. SSA is thought to be the very basis of a large number of humans' cognitive activities including learning, perceptual priming, or even face representation (Grill-Spector et al., 2006), and could therefore represent a key mechanism of attention decrement as well. Remarkably, in humans' cognitive activities, SSA can have either a positive effect on behavioral performance (*i.e.*, the neural response to a given stimulation is diminished but behavioral performance is improved, such as in perceptual priming; Wiggs and Martin, 1998) or a detrimental effect on behavior, as it is the case in perceptual habituation. In the former case, SSA has been shown to be resistant to changes in the features of the presented stimulus, the neural response and behavioral performance improvements being persistent even when the size or the color of a repeated stimulus is manipulated (Wiggs and Martin, 1998). In the latter case, however, the detrimental effects on both neural response and behavioral performance remain exclusively specific to the repeated stimulus (Netser et al., 2011; Thompson and Spencer, 1966). Changing sensory stimulation leads then to a sensitization, also called dishabituation, which is associated with a recovery from the decrease in the neural response (Thompson and Spencer, 1966). However, the decrease in the early VEP observed by Boksem et al. (2005) throughout a sustained attention task occurred independently of stimulus, for both the target and the non-target stimuli. The question arises then of whether a less stimulus-specific adaptation could be involved at the

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[62] As Grill-Spectro et al. (2006) noted SSA has been also referred to as neural priming (Maccotta and Buckner, 2004), repetition suppression (Desimone, 1996) and decremental responses (Brown and Xiang, 1998).

neural level so as to explain the decreases in perceptual sensitivity and this overall decline in sensory cortices' neural response observed with TOT.

Inhibition of return (IOR) represents an important attentional process by which objects and locations that have just been processed are less effectively processed in the near future. In 1984, Posner and Cohen strikingly discovered that motor responses to targets presented at the same location as a previously presented target were delayed. These behavioral findings have been numerously replicated in visual, auditory and tactile modalities (Fuentes et al., 2012) and using both manual and occulo-motor responses (Briand et al., 2000). Furthermore, IOR has been found to occur in covert and overt orienting of attention (McDonald et al;, 2009), and both for foveal and extrafoveal locations (*e.g.*, Mele et al., 2012). Finally, IOR has been demonstrated as occurring for non-spatial properties of an object such as line orientation, shape or color (Law et al., 1995; Zhou and Chen, 2008). The IOR process appears to be involved in a multitude of conditions, and this kind of inhibitory processes may represent a substantial aspect of humans' cognition. In this vein, IOR has been considered as an artifact of human evolution in that it may reflect humans' and primates' foreaging tactics (Klein, 2000). Thus, why an IOR-like[63] process might not be involved in sustained attention as well? During sustained attention tasks, a given stimulus (or two stimuli in Go-NoGo tasks) is (are) presented at the center of a screen. Participants have then to respond, usually by a manual key press, as fast as possible to target stimuli. These targets are presented at the same location of the screen (*i.e.*, usually the center), potentially leading to an increasing spatial IOR-like process throughout TOT. Further, in detection tasks the stimuli attributes are basically unchanging, which could lead to an object-based IOR-like process and additive effects of spatial and non-spatial IOR have been demonstrated in the literature (Fuentes et al., 2012). The neural mechanisms underlying IOR have been subjected to numerous investigations. A recent literature review of the state-of-the-art (Fuentes et al., 2012) describes an active inhibition of the sensory areas involved in the task through top-down afferent signals originating from PFC and parietal cortices. The involvement of such an active inhibitory mechanism during sustained attention could explain the overall decrease in perceptual sensitivity and the increase in RT observed over time.

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[63] I will exploit the terms "IOR-like process" in order to describe the potential active inhibition of sensory neural structures in sustained attention, because we cannot directly consider that IOR occurs during sustained attention tasks given that IOR is a stimulus-locked mechanism (Klein, 2000). My argument is that we should consider that the inherent ability of humans to inhibit the reexamination of a stimulus or location that has just been processed is likely to be involved during sustained attention tasks as well.

Overall, the hypothesis of the involvement of an IOR-like process during sustained attention seems to be supported by behavioral data (*i.e.*, behavioral markers of IOR and of attention decrement are similar) and by a brief analysis of the paradigms exploited in both the sustained attention and the IOR literature. As a by-product of evolution, humans have developed this amazing ability to inhibit the reexamination of perceptually irrelevant stimulations from the environment. Remaining focused on a perceptually unchanging environment, such as the train driver in one of the examples of Robertson (2003, see p. 93), goes against this naturally acquired attentional function, which could explain the subjectively perceived high level of effort expenditure experienced following sustained attention tasks as well as the increased activity in attention-related brain structures with TOT. One may thus hypothesize that, as time elapses, an increasing level of inhibition should be observed in sensory structures involved in the sustained attention task. This hypothesis is tested in **Chapter II**.

Focused sensory attention involves a facilitation of sensory neurons coding for the attended stimulus. Attention decrement might apparently involve the inverse pattern, which would explain the decrease in perceptual sensitivity and the increase in RT associated with the phenomenon. Similarly, focused motor attention involves a facilitation of motor neurons coding for the upcoming movement. One may then intuitively and logically suggest that attention decrement should involve a disengagement of these motor neurons coding for the upcoming movement. In this sense, the increase in RT characterizing the attention decrement phenomenon would result from both a sensory and a motor dysfacilitation. Strikingly, however, some indices in the literature seem to suggest that motor neural structures' activity increases with TOT. This observation, which could be related to the increased motor impulsivity with attention decrement, is discussed next.

2.2.3.2. Attention decrement: what role for the motor neural structures' activity?

A few lines above, I mentioned that an increased inhibitory activity in the sensory cortices could account for the absence of detection of critical signals by the train driver in the example given by Robertson (2003). But what if, as Robertson argued, the absence of response of the train driver to these critical signals was related to an incapacity to withhold the currently realized set of action? As previously mentioned, a typical signature of attention decrement consists of an increased inability to inhibit current actions. Intuitively, it may be assumed that such a lack of inhibition reflected at the behavioral level should be associated with a disinhibition - or an increased facilitation - of the neurons coding for the currently "selected" movement with TOT. However, such an hypothesis has yet to be tested. Some studies have reported an increased activity of the basal ganglia with TOT in healthy (normal) (Coull et al., 1998) and in TSD subjects[64] (Drummond et al., 2005). Further, two trial-by-trial analyses (Weissman et al., 2006; Yarkoni et al., 2009) have described an increased fMRI-measured event-related M1 activity associated with longer RT. The interpretation provided by Drummond et al. (2005) is that "*poor performance after TSD may elicit a subsequent attentional recovery that manifests as greater activation within the same regions normally responsible for fast RT*". Similarly, Weissman et al. (2006) concluded that the motor structures belong to those which present an over-engagement potentially to overcome the decreased sensory areas' activity related to momentary lapses in attention (please see p. 110). Finally, another group of results comes from the attention-deficit hyperactivity disorder (ADHD) literature where it has been numerously described that children with ADHD presented significant decrease in the level of TMS-measured ICI (Buschman and Miller, 2007; Gilbert et al., 2005, 2011; Heinrich et al., 2014; Hoegl et al., 2012; Moll et al., 2000, 2001) compared to age-matched control subjects, either at rest or during motor control and Go-NoGo tasks.

3. Cognitive Neuroscience of attention decrement: issues and hypotheses

3.1. Current issues

Since the reawakening of interest in attention research in the field of psychology in the late 1940s (*i.e.*, with the work of Mackworth, 1948), substantial advances have been made regarding our understanding of this vital cognitive function. As I have described in the first

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[64] In Drummond et al. (2005) TSD subjects did not sleep in 36 hours before performing the PVT (please see p. 105).

section of this chapter (*i.e.*, Section *1. What is "Attention"?*), advances in Cognitive Neuroscience have allowed us to better understand how focused attention functions under conditions of full capacity. More precisely, a better understanding of focused motor and sensory attention has arisen from studies investigating how those functions are expressed within motor and sensory cortices, respectively: focused attention facilitates certain actions and perceptions at the expense of others.

In contrast, the neural underpinnings of the sensory-motor deficiencies associated with attention decrement remain still unclear. In other words, we now have a clear picture of how focused attention manifests in sensory and motor cortices but we do not absolutely know how attention decrement does. We are currently able to precisely describe how, at the neural level, focused attention governs humans' perceptions and actions, but we are totally unable to depict how attention decrement disrupts these perceptions and actions. One explanation for the current lack of knowledge on this topic is that the two proposed theories of attention decrement (*i.e.*, the resources and the mindlessness theories) are centered on the control processes underlying sustained attention, thus leaving little opportunity for the investigation of the sensory-motor neural correlates of the phenomenon.

3.2. Objectives of the current thesis

The history of Cognitive Neuroscience has compellingly proven that investigating the sensory-motor neural correlates of attention-related functions represents a stepping stone towards a better understanding of how these functions alter and affect humans' actions and perceptions. Given that attention decrement is characterized by sensory-motor deficiencies, investigating the sensory-motor neural correlates of the phenomenon could prove to be an effective way towards better understanding it. In this context, the question that arises and that is at the center of the first part of this thesis[65] is:

What are the sensory-motor neural correlates of attention decrement?

Further, a second objective of the first part of this thesis is to identify the adaptation of attention-related cortical areas to TOT. Such an investigation may provide further data so as

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[65] That is, *Part I - Cognitive Neuroscience*.

to better understand how sensory-motor neural structures act in concert with attention-related ones during sustained attention tasks.

3.3. Hypotheses

Based on the literature, two main patterns of neural activity are expected to characterize the occurrence of attention decrement. First, an active inhibitory neural mechanism is expected to occur in the sensory cortices involved in the task. This active inhibitory neural mechanism should occur early in the task, should be restricted to the given sensory areas and should be associated with a decrease in the sensory evoked neural response (*i.e.*, sensory ERP). This hypothesis is tested in **Chapter II**. Second, an over-facilitation of the motor neural structures is expected with TOT. This over-facilitation of the motor neural structures should occur later in the task and should not be restricted to the motor areas but should be associated with an over-engagement of attention-related cortical areas. This hypothesis is tested in **Chapter III**. In other words, the first part of this thesis tests the hypothesis that while focused attention is expressed in a similar way in sensory and motor neural structures, attention decrement is expressed in opposing ways in these neural structures.

Chapter II

Visual attention decrement

"In Nature, organisms deal with multiple locations and objects. By keeping track of the locations and objects that prove to be irrelevant, they prevent useless reexaminations and maximize survival."

Luis J. Fuentes (2012)

*F*oreword: context of the present study

The study presented in the current chapter aimed at investigating the manifestation of attention decrement within the sensory neural structures involved in a sustained attention task (*i.e.*, visual cortices in this study). Please however note that the data exploited to investigate this question originate from a larger data set recorded in the context of a collaborative project to which I contributed and which aimed at investigating the potential relationships between attention and temporal expectations in visual perception. In this project, participants came twice to the laboratory to perform a sustained attention task under two different conditions. The two sustained attention tasks performed differed in the structures of the presented ISI. In one condition, the ISIs were randomly distributed to impede expectation effects (*i.e.*, white noise or WN condition) while in the other condition, the ISI exhibited long-term correlations, inducing temporal expectations. We thus manipulated TOT-related changes in attention and temporal expectations orthogonally and subsequently assessed how it affected behavioral performance and several components of the VEP. This study has been published as a peer-reviewed article (Derosière et al., In Press[66]).

In the present chapter, I only exploit the EEG and behavioral data from the WN condition to investigate *how does attention decrement affect the sensory neural structures' activity*. Please note that, as the experimental protocol and the EEG data preprocessing was the same for the present study as for the previously mentioned submitted work, some parts of this chapter originate from the original research article (*i.e.*, Derosière et al., In Press).

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[66] **Published as**:
Derosiere G, Farrugia N, Perrey S, Ward T, Torre K. (In Press). Expectations induced by natural-like temporal fluctuations are independent of attention decrement: Evidence from behavior and early visual evoked potentials. *NeuroImage, doi: 10.1016/j.neuroimage.2014.09.015.*A full version of this research article is available in Appendix A.

1. Introduction

Focused sensory attention represents a vital cognitive function that facilitates the processing of a given sensory information at the expense of others. Accordingly, decrements in focused attention severely impact humans' efficiency in sensory information processing, as usually manifested by decreases in perceptual sensitivity (*e.g.*, Helton and Russel, 2011) and increases in RT over TOT (*e.g.*, Lim et al., 2010). Despite the crucial negative consequences of attention decrement on perception, so far, little is known about the neural underpinnings of TOT-related sensory deficiencies. Investigating the neural correlates of such TOT-related sensory deficiencies represents a stepping stone towards a deeper understanding of the attention decrement phenomenon.

Focused sensory attention acts as a "*sensory gain mechanism*" (Hylliard et al., 1998): it induces an increase in the pre-stimulus excitability (*e.g.*, Kastner and Ungerleider, 2000) and in the response (*e.g.*, Luck et al., 1997) of the neurons specifically coding for the attended stimulus. Given this, one may suggest that attention decrement should involve a less efficient *sensory gain mechanism*. It indeed does. Boksem et al. (2005) and Faber et al. (2012) showed a decrease in the early sensory components of the VEP with TOT during sustained attention discrimination tasks. Further, their results are in accordance with the study of Weissman et al. (2006) who demonstrated, by means of a trial-by-trial analysis, an fMRI-measured decrease in the response of the visual cortices associated with momentary lapses in attention. The interesting question arises then of *why* such a disengagement of the sensory neural structures occurs with TOT.

As the paragraph quoted on this chapter's front page states "*By keeping track of the locations and objects that prove to be irrelevant, [organisms] prevent useless reexaminations and maximize survival*" (Fuentes, 2012). This idea appears to hold useful as an explanation for attentional phenomenon in humans, the IOR mechanism often taken as evidence of this ability (Klein, 2000). Also, as I argued in Chapter I (please see pp. 113-114), such an inhibitory neural mechanism may occur during sustained attention tasks[67], given the repetitive characteristics of sensory stimulation in such tasks. One typical signature of neural inhibition

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[67] Or vigilant attention, or else vigilance task. I do not make any distinction here as the hypothesis applies to these different types of task.

in humans is the EEG-measured level of α-band power. As has been described for instance in Figure 1.8, in a study by Snyder and Foxe (2010), focusing visual attention on the color of a stimulus induces an increase in oscillatory activity in the α-band within the dorsal visual stream, responsible for location-based visual processing. Further, the authors also demonstrated that focusing visual attention on to location-related features of the same stimulus induced an increased oscillatory activity in the α-band within the ventral visual stream, responsible for processing object-based features. In a relatively recent review, Jensen and Mazaheri (2010) described α oscillations as a signature of an active inhibitory mechanism, involving GABAergic inter-neuronal networks (Jones et al., 2000; Lorincz et al., 2009). According to the authors, oscillatory activity in the α-band represents a signature of a "*gating-by-inhibition mechanism*" which is at the very basis of information processing. The higher the level of oscillatory α activity in a given area, the more the gate is closed.

So what if, as time elapses during sustained attention tasks, the sensory gates get progressively closed? An investigation conducted by Huang et al. (2007) provides substance to this hypothesis. In this study, one of the tasks required participants to drive for one hour in a simulation display and to keep the vehicle straight while it was linearly pulled into the opposite lane every three to seven seconds. The authors notably focused their EEG analyses on periods when high levels of errors momentarily occurred as measured by lane deviation. Based on source localization and ICA, they observed that periods with high levels of errors occurred concomitantly with an increased neural activity characterized by an independent component, localized within the visual cortices and specifically present in the α-band as compared to the other frequency bands. These findings suggest that momentary decreases in behavioral performance during sensory-motor tasks are associated with an increased level of α activity, specifically in the sensory areas involved in the task. The authors later replicated these results using other experimental conditions (Huang et al., 2008). In the same vein, Newman et al. (2013) recently transferred the pre-stimulus EEG frequency analyses that are usually performed in phasic alertness protocols (*e.g.*, Thut et al., 2006) to the study of TOT-related changes in oscillatory activity occurring during a 48-min duration visuo-spatial RT task. Using this approach the authors have been able to demonstrate that the pre-stimulus level of α activity increased with TOT within a set of pre-defined parieto-occipital regions of interest (ROI). These results were associated with a TOT-related degradation in behavioral performance (*e.g.*, an overall increase in RT), and suggest that the level of inhibition in the sensory areas involved in the task indeed increases while the level of attention decreases over time. However, in this study, no analysis has been performed regarding other scalp electrodes in order to depict whether *(i)* the increase in α activity was specific to the visual cortices or *(ii)* was significantly higher at the occipital than at other scalp locations. To put it succinctly, the studies by Huang et al. (2007, 2008) demonstrate that momentary decrement in behavioral performance are associated with increased level of α activity specifically within the visual cortices, while Newman et al. (2013) reported an increased level of α activity in the visual cortices with TOT but did not test whether this increase was specific in terms of scalp location. Overall, one may hypothesize that the TOT-related decrement in behavioral performance might be associated with a region-specific increase in oscillatory activity in the α-band, located in the sensory cortices involved in the task.

This hypothesis was tested in the present study. To do so, we exploited a Monte-Carlo permutation analysis allowing the identification of the precise spatial scalp location where significant increases in α-band occurred over TOT (Maris and Oostenveld, 2007). As Newman et al. (2013), we based the analysis on changes in pre-stimulus oscillatory activity in the α-band as occurring throughout TOT in a sustained attention RT task. Further, we examined how such changes evolved in concert with expected decreases in the neural response of visual cortices as assessed by the early components of the VEP.

2. Materials and methods

2.1. Participants

Nineteen healthy subjects participated in this study (aged 26.6 ± 4.5 years, height 178.4 ± 6.6 m; body weight 70.9 ± 8.3 kg). All subjects were right-handed according to the Edinburgh Questionnaire (Oldfield, 1971). To control for any potential confounds, baseline levels of sleepiness were reported by the subjects using the Epworth Sleepiness Scale (ESS; Johns, 1991). Subjects having a score value higher than 9 on the ESS were not included in the study. Subjects' habitual caffeine intake had to be less than 5 cups per day and subjects had to be careful of the number of cups taken in the day before the experimental session. No subject declared any neurological, respiratory, and cardiovascular disease or medication, which might affect brain/cognitive functions. Each subject provided written informed consent prior to participation in the study. All procedures were approved by the local ethics committee (CPP Sud-Méditerranée II, number 2010-11-05) and complied with the Declaration of Helsinki for human experimentation.

2.2. Experimental design

Experiments were conducted in a quiet and dimly-lit room. The subjects were seated at a table in front of a 22-inch LCD monitor positioned at a distance of 1 m from the subject's eyes which was used to display the target stimuli during the sustained attention RT task. The left and right forearms were rested upon the surface of the table with the palms facing the table. A response switch box (BioSemi, Amsterdam, the Netherlands) was positioned under the dominant (*i.e.*, right) hand with the response button under the index finger.

2.3. Experimental protocol

First, a simple visual RT task of 1-min duration was performed in order to familiarize the subjects with the paradigm. The visual target stimulus consisted of a white cross (size: 13×13 cm) displayed for 10 ms at the center of a black screen. Stimulus presentation was controlled using the Presentation software package® (version 16.2, www.neurobs.com) on a standard Microsoft Windows computer system. Subjects were required to push the response button by flexion of the index finger as fast as possible in response to the visual stimulus. The mean of the generated ISI was set at 2,000 ms, with a coefficient of variation of 30 %. Once the familiarization phase realized, subjects were instructed to rest for 4 minutes (2 minutes eyes open followed by 2 minutes eyes closed) in order to stabilize the EEG signals. At the end of the resting phase, subjects performed the sustained attention task. Characteristics of the visual stimuli and ISI were the same as described above but the entire task comprised 513 stimuli. Once the entire experiment was completed, we verified that the experimental ISI series actually presented the properties of the input series. Measured ISIs were of 2,140 ± 20.5 ms (mean ± SD), so that the sustained attention task duration was 18"30 min on average (*i.e.*, 513 × 2,140 ms).

2.4. Data collection

EEG was recorded continuously and amplified using a BioSemi Active-Two system (BioSemi B.V., Amsterdam, The Netherlands) with 32 Ag/AgCl active electrodes relative to a scalp reference. EEG was recorded continuously from DC to 2,048 Hz. BioSemi systems work with a "zero-ref" setup with ground and reference electrodes replaced by a Common Mode Sense/Driven Right Leg circuit (CMS/DRL; for further information, please refer to http://www.biosemi.com/faq/cms&drl.htm). The 32 EEG electrodes were placed according to the International 10-20 system (Jasper, 1958) by means of an electrode cap. CMS and DRL electrodes were placed at the scalp level between C3 and Cz, and Cz and C4, respectively. Motor responses were recorded using the response switch box. Stimuli and motor triggers were recorded through the A/D box of the BioSemi system.

2.5. Data analysis

2.5.1 Behavioral data

All data were processed through Matlab and using the Fieldtrip toolbox (Nijmegen, Amsterdam; Oostenveld et al., 2011). The RT was measured as the time between the onset of the visual stimulus (target stimulus) and the onset of the motor response. Responses were considered valid if the response button was pressed after 150 ms following stimulus onset. Other responses were considered as reflecting anticipatory motor response and thus discarded from further analysis. A similar cut-off time window has been applied in previous RT studies (*e.g.*, Faber et al., 2012). On this basis, we calculated for both conditions the average RTs obtained for six non-overlapping blocks of 3 min duration: 0 to 3 min, 3 to 6 min, 6 to 9 min, 9 to 12 min, 12 to 15 min and 15 to 18 min of the task. For each block, omissions and commissions were counted as well. Omissions were defined as stimuli that were not followed by any motor response and commissions were defined as motor responses having occurred while no visual stimulus occurred.

2.5.2. EEG data

2.5.2.1. EEG data preprocessing

The continuous EEG recordings were downsampled to 512 Hz and off-line segmented in 1,400 ms epochs starting 400 ms before and finishing 1,000 ms after stimulus onset. To ensure good quality ERPs and pre-stimulus oscillations analyses, several inclusion criteria were applied to the trial selection such that trials comprising *(i)* a motor response during the pre-stimulus period (*i.e.*, during -400 and 0 ms), *(ii)* more than one motor response between stimulus onset and + 600 ms (*i.e.*, fast double clicks) or *(iii)* a motor response between stimulus onset and + 150 ms, were excluded. On the defined epoch of interest, we applied an automatic artifact rejection algorithm which identified and rejected large jump and muscle artifacts (*i.e.*, originating from EMG sources) by means of thresholding the z-transformed values of band-pass filtered and raw data. Cutoff z-values were determined based on visual inspection of five subjects' recordings, and set at 25 and 15 for jump and muscle artifacts, respectively, and using band-pass (110 to 140 Hz) filtered data for detecting muscle artifacts. These automatic steps, coupled with visual inspection of remaining trials, were carried out to remove trials with large artifacts. The remaining trials were high-pass filtered using a cutoff frequency of 0.5 Hz, in order to remove slow drifts. Subsequently, the ICA technique was applied in order to remove common artifacts from the recordings (Delorme et al., 2007). Careful joint inspection of the power spectrums, scalp topographies and ERPs of components facilitated the evaluation of specific components for artifact rejection. Once undesirable components were identified, the EEG signals were back-projected based on the other independent components. The remaining data were screened manually for residual artifacts and we subsequently applied baseline correction on the artifact-free trials.

2.5.2.2. Event-related potential

Average ERPs were computed for every 3-min block (*i.e.*, 0 to 3 min, 3 to 6 min, 6 to 9 min, 9 to 12 min, 12 to 15 min and 15 to 18 min of the task). We computed ERPs by pooling the values of neighboring electrodes within a posterior ROI, identified on the basis of the scientific literature (Hillyard et al., 1998; Di Russo et al., 2003, 2005, 2008; Smit et al., 2007), and of the measured scalp topographies. The P1 and N1p components were analyzed in this posterior ROI which included the following parieto-occipital electrodes: O1, O2, PO3, PO4, P7, P8, Oz. Finally, a peak detection algorithm was applied to the individual ERPs in order to extract peak amplitude and latency values for the components of interest. The time ranges used for identification of P1 and N1p peaks were determined from a visual inspection of subjects' ERPs and through known results in the literature (*e.g.*, Munoz-Ruata et al., 2010; Smit et al., 2007) and were of 70-120 ms and 120-190 ms post-stimulus, respectively. All detected peaks were verified by visual inspection to confirm that each computed individual value was well-supported from the individual graphs. These confirmed P1 and N1p peak amplitudes and latencies were recorded for subsequent statistical analysis.

2.5.2.3. Time-frequency analysis

Average time-frequency analyses were computed for every 3-min block (*i.e.*, 0 to 3 min, 3 to 6 min, 6 to 9 min, 9 to 12 min, 12 to 15 min and 15 to 18 min of the task). We performed the time-frequency analyses on a time window of - 400 ms to 0 ms with respect to target stimuli onset. We exploited Morlet's wavelets in order to estimate the time-frequency representation with an appropriate scale, which offered a good relation between frequency and time-resolution. A special focus has been made on the changes in spectral power in the range of 7 - 13 Hz (α-band). Subsequently, Monte-Carlo permutation analyses were performed in order to test for any effect of TOT on spectral power in the α-band among the 32 EEG electrodes. Monte-Carlo analyses are described next.

2.6. Statistical analysis

2.6.1. Monte-Carlo permutation analyses on pre-stimulus α-band power

The use of Monte-Carlo permutation analyses on EEG data has been proposed by Maris and Oostenveld (2007) in order to solve the multiple comparison problem (MCP), typically encountered in neuroimaging data set where brain-originating signals are sampled in multiple time points, spatial locations and frequency bands. In brief, when applied on time-frequency data, the method facilitates the identification of the probability of significant differences between two or *n* conditions as reflected in three dimensional time-points (*i.e.*, the dimensions being time, frequency and electrode position).

The analyses presented in this chapter were exclusively based on a frequency of 10 Hz in order to reduce the computational cost. We tested for significant differences between pairs of two-dimensional (*i.e.*, time and electrode positions) time-points: each two-dimensional time-point of the block 1 (*i.e.*, 0 to 3 min of the task) was statistically compared to the corresponding two-dimensional time-point of the other blocks (*i.e.*, 3 to 6 min, 6 to 9 min, 9 to 12 min, 12 to 15 min and 15 to 18 min of the task) as follows[68]. In a first step, a student t-test for dependent samples was performed for each pair of two-dimensional time-points. t-values exceeding an alpha level of p = .05 were selected and clustered in connected sets based on spatial and temporal adjacencies. Cluster level *t*-values were subsequently computed as the sum of each individual *t*-value. In a second step, Monte-Carlo permutation analyses were performed. The trials of each block were first grouped together in a single data set. Then, based on this combined data set, trials were randomly selected until reaching as many as trials as there were in condition 1 (*i.e.*, block 1, extending from 0 to 3 min of the task). This pool of randomly selected trials composed subset 1 while the remaining trials constituted subset 2, resulting in a so-called "random partition". Based on random partition so obtained, a t-test was performed in the exact same manner as during the first step, that is: *(i)* student t-test for dependant samples was first performed for each pair of two-dimensional time-points as obtained from subset 1 and subset 2; *(ii)* t-values exceeding an alpha level of p = .05 were selected and clustered in connected sets based on spatial and temporal adjacencies; *(iii)* cluster level t-values were subsequently computed as the sum of each individual t-value. The random

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[68] For further information about the method, please refer to the original paper of Maris and Oostenveld (2007), or to the Fieldtrip website at: http://fieldtrip.fcdonders.nl/tutorial/cluster_permutation_freq?s[]=ft&s[]=freqstatistics

partitioning and the subsequent calculation of the cluster level t-values were re-iterated 500 times and a histogram of the t-values was then constructed. The proportion of random partitions that resulted in larger t-test values than the observed one was finally calculated. This proportion represents the *Monte-Carlo significance probability*, also called *p-value*. If, for a given two-dimensional time-point, less than *5 %* of the random partitions resulted in a larger t-test value than the observed one, then it is said that this time point is significantly different at *p <. 05* between the two compared experimental conditions (*e.g.*, block 1 and block 2). If, for a given two-dimensional time-point, less than *1 %* of the random partitions resulted in a larger t-test value than the observed one, then it is said that this time point is significantly different at *p <. 01* between the two compared experimental conditions. The whole procedure has been also performed with 1,000 permutations so as to further increase the accuracy of the Monte-Carlo approximation. This procedure allowed us to check whether the significant differences identified at any given electrode location and time point were actually robust to an increase in the number of permutations.

2.6.2. ERP components and behavioral data

Statistica software (version 7.0, Statsoft, Oklahoma, USA) was used for analyses. All data were examined for normality and homogeneity of variance using Skewness, Kurtosis, and Brown-Forsythe tests. P1 and N1p peak amplitudes and latencies as well as RT data presented normal distributions and homogeneity of variance. Therefore, two-way repeated-measure ANOVAs were used to test for any significant effects of TOT on these data (*i.e.*, 0 to 3 min, 3 to 6 min, 6 to 9 min, 9 to 12 min, 12 to 15 min and 15 to 18 min of the task). When appropriate, the Fisher's LSD post-hoc test was used to detect paired differences. Because of the non-normal distribution of the omissions and commissions samples, Friedman nonparametric ANOVAs were performed to test for the significant effects of TOT on these data. The significance level was set at $p < 0.05$. Data are presented mean ± standard deviation (SD), unless specified.

3. Results

3.1. Behavioral results

A significant increase in RT ($F_{5,90} = 9.5$; $p < .001$) and in the number of omissions ($Fr_{5,19} = 16.6$; $p < .01$) was observed as a function of TOT. No significant effect of TOT was found on commissions ($Fr_{5,19} = 6.9$; $p = .23$). Behavioral results are presented in Figure 2.1.

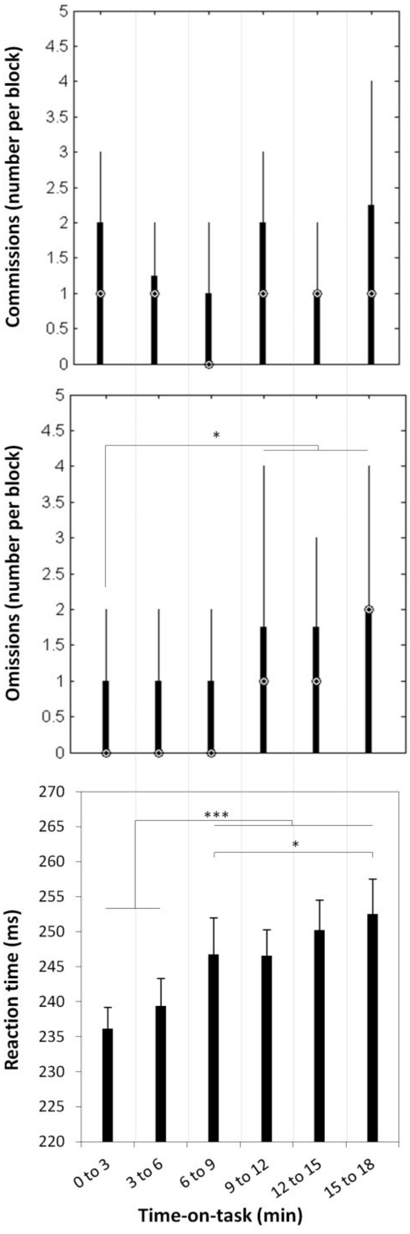

Figure 2.1: TOT effects on behavioral performance during a 18-min duration sustained attention task. The number of commissions (*i.e.*, upper graph) and omissions (*i.e.*, middle graph) are represented through box and whisker plots where dots represent medians, boxes represent the inter-quartile range and whiskers represent the maximum values for each sample. The middle and lower graph evidence the significant effects of TOT on omissions and RT variables, respectively. * $p < .05$; *** $p < .001$. Vertical bars represent standard-errors.

3.2. EEG results

3.2.1. P1 and N1p components of the visual evoked potential

The P1 component occurred at 98 ± 11 ms post-stimulus on average. No significant effect of TOT was found on P1 amplitude ($F_{5,85} = 1.9$; $p = .11$) and latency ($F_{5,85} = 0.6$; $p = .71$). The N1p component occurred at 157 ± 12 ms post-stimulus on average. N1p amplitude significantly decreased ($F_{1,26} = 5.5$; $p < .05$), while N1p latency significantly increased as a function of TOT ($F_{2,36} = 17.5$; $p < .001$). These results are presented in Figure 2.2.

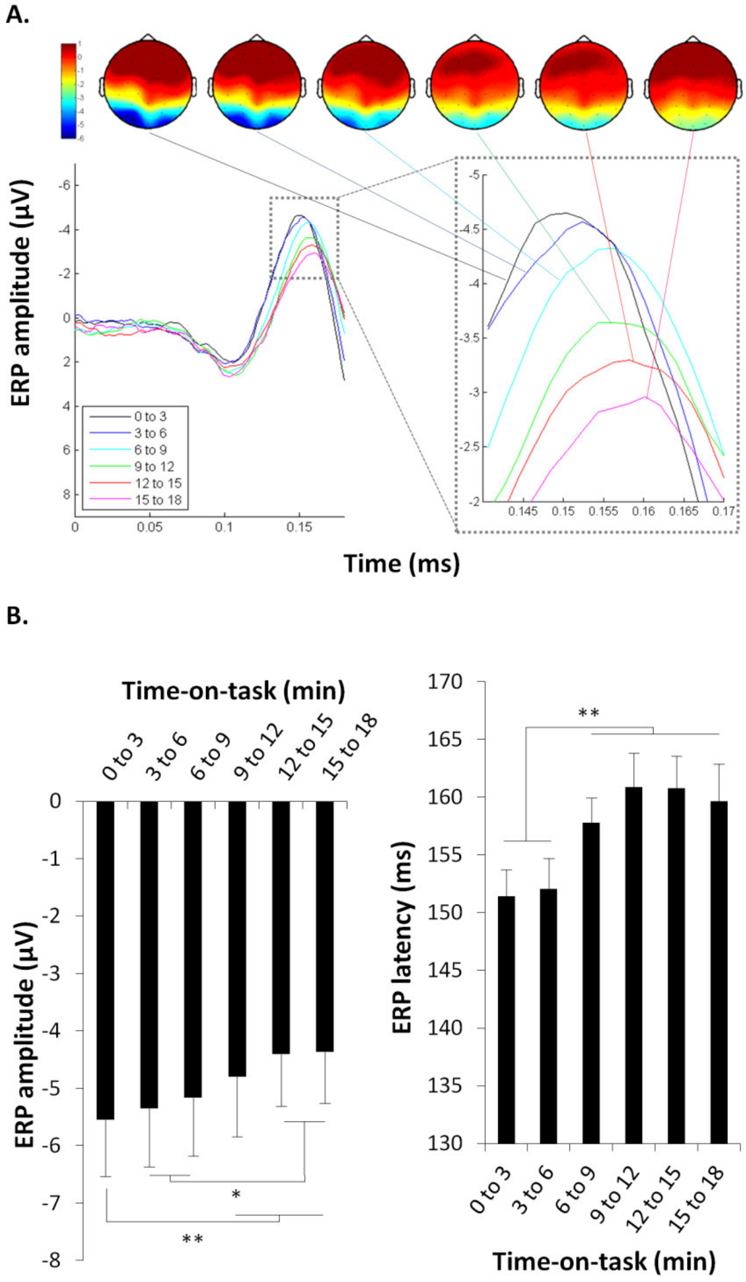

Figure 2.2: TOT effect on the N1p component of the visual evoked potential. A. Grand-averaged ERP representations (n = 19). *Top*: scalp topographies of the grand-averaged N1p component for each 3-min duration block (1st block on the left, last block on the right. *Bottom*: Grand-averages from the parieto-occipital ROI (please refer to the text for more information) for each 3-min duration block. These grand-averaged representations clearly show the decrease in N1p amplitude, and to a less extent the increase in N1p latency, with TOT. Also, the lack of decrease in P1 amplitude can be observed on the bottom-left graph. **B. Statistical results on the N1p data.** * p < .05; ** p < .01. Vertical bars represent standard-errors.

3.2.2. Pre-stimulus α-band power

Monte-Carlo analyses revealed a significant increase in the level of α-band (10 Hz) power during the pre-stimulus period with TOT, occurring specifically over the visual (*i.e.*, occipital) cortical areas. Moreover, this increase in α-band power occurred from the very beginning of the task (*i.e.*, after the first 3-min duration block). Further details are provided in Figure 2.3.

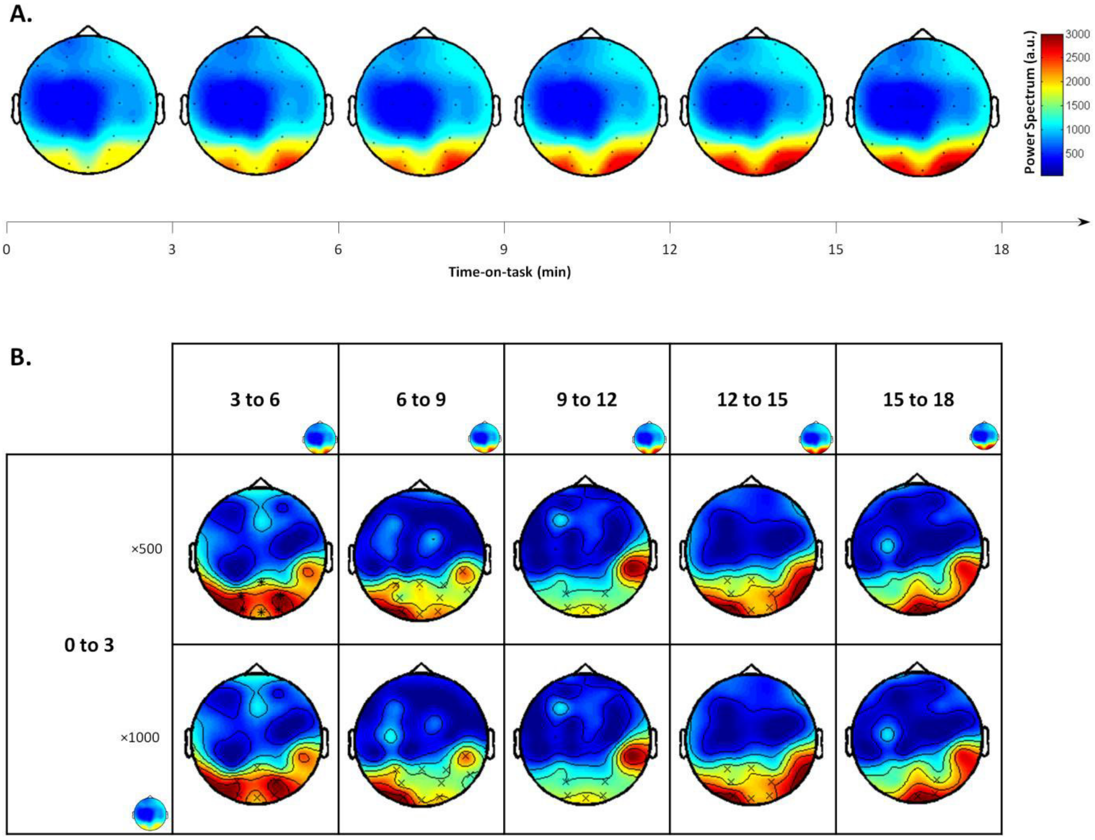

Figure 2.3: TOT effects on α-band power over scalp topographies. A. Scalp topographies of grand-averaged α-band power (at 10 Hz) as a function of TOT. The topographies clearly show an occipital increase in α-band power with TOT. However, the specificity of the localization has to be statistically tested by Monte-Carlo permutation analyses. **B. Monte-Carlo permutation results of the TOT effect on the pre-stimulus level of α-band power (t = - 125 ms relative to stimulus onset).** The first 3-min duration block has been compared with the other blocks. Colors represent the level of the t-values as obtained following the paired comparisons of each block with the first 3-min duration block (*i.e.*, with red representing the highest level of significant t-values). The superposed marks represent the results of the Monte-Carlo permutation analyses, depicting the locations where significant differences have been identified. $^{\times}$ p < .05; * p < .01. ×500 and ×1000: analyses performed with 500 and 1,000 permutations, respectively. Overall, increasing the number of permutations did not affect the cluster results, apart from a decrease in significance level for the effect observed between the first and the second blocks. That the increase in the number of permutations did not substantially affect the obtained cluster results demonstrates the robustness of the significant increase in α-band power with TOT over the visual cortices.

4. Discussion

The aim of the present study was to highlight the sensory neural correlates of attention decrement. Attention decrement occurred as manifested by the significant increase in RT and in omissions over TOT. As hypothesized, our Monte-Carlo analyses revealed a significant increase in oscillatory activity in the α-band during the pre-stimulus period, specifically occurring within the visual cortices. Further, this increase in α activity occurred very early in the task, suggesting an early involvement of inhibitory neural mechanisms during sustained attention. In concert with these pre-stimulus changes in neural activity, we demonstrated a decrease in amplitude and an increase in latency of one of the sensory components of the VEP, namely N1p. Before focusing on a discussion of these TOT-related changes in neural activity, a number of relevant behavioral considerations is discussed.

4.1. Sensory-motor behavioral signatures of attention decrement

In the present study, attention decrement was manifested - at the behavioral level - by significant increases in both the RT and the number of omissions, which occurred after 6 and 9 min of the task, respectively. One may further notice that RT continued then to increase until the end of the task (please see Figure 2.1). Such results are in accordance with previous observations in the literature that attention decrement is associated with decreases in perceptual sensitivity (*e.g.*, Helton and Russel, 2011), and longer response times to imperative signals (*e.g.*, Lim et al., 2010). This is however worth mentioning that the task exploited in the current study failed to induce any increase in the number of commissions with TOT. Actually, as argued by Robertson and colleagues (Manly et al., 1999; Robertson et al., 1997; Robertson, 2003) and as already discussed in Chapter I (please refer to part 2.1 of Chapter I, p. 94), the occurrence of the different behavioral markers of attention decrement mostly depends on the task characteristics. As such, Go-NoGo tasks with rarely occurring NoGo events (*i.e.*, such as the SART) are more appropriate to induce increases in the number of commissions with TOT (Robertson et al., 1997). However, in the current study, we have voluntarily exploited a simple RT task (*i.e.*, comprising exclusively Go stimuli) so as to allow participants to fully prepare for the upcoming stimulus during ISIs. Using a Go-NoGo task would have involved the concomitant interplay of facilitatory and inhibitory neural mechanisms, which could have been a confounding factor in the interpretation of the results regarding the TOT-related changes in α activity. Thus, based on this simple RT task, we have been able to provide evidence that the level of inhibitory neural activity increased with TOT within sensory cortices while no distracter-related inhibition was required by the task. These results are examined below.

4.2. Attention decrement neural signatures: evidence for an early increase in alpha activity within sensory cortices

The present study reports interesting results as regards to the pre-stimulus changes in neural activity within sensory cortices during sustained attention. By exploiting Monte-Carlo permutation analyses, we were able to *(i)* confirm that α activity significantly increases in the pre-stimulus period with TOT and even more interestingly *(ii)* determine that this significant increase in α activity was restricted to an occipital cluster. These results are in line with the studies of Huang et al. (2007, 2008) and Newman et al. (2013) discussed in the introductory section of the current chapter. Further, one may notice that the increase in α activity occurred very early during the sustained attention task, preceding the significant increases in omissions and in RT which manifested later in the task (see Figure 2.1). Therefore, it may be assumed that the increased level of inhibition within the sensory cortices could represent a potential neural cause of the behavioral deficiencies characterizing attention decrement. In this sense, the involvement of an IOR-like mechanism in attention decrement is highly plausible. The lack of changes in perceptual stimulation during sustained attention tasks may lead to an early inhibition of the sensory cortices, the sensory information repeatedly presented in such tasks proving to be irrelevant. What is more, the current results and interpretations are totally in accordance with the mindlessness theory of attention decrement presented in Chapter I (see p. 107). Indeed, the increased level of inhibition within the sensory cortices may explain why humans progressively turn themselves to self-centered matters as time elapses during perceptually-unchallenging sustained attention tasks (Braboszcz and Delorme, 2011). In the same vein, the present interpretations are fully in accordance with the observation that sustaining attention to simple tasks is subjectively perceived as highly challenging. Roughly, one may suggest that trying to sustain attention in such perceptually unchallenging tasks goes actually against a naturally acquired IOR-like mechanism that prevents us for reexamining irrelevant information over several iterations. Accordingly, in the previously mentioned VEP study of Boksem et al. (2005) the authors also reported *(i)* an overall increase in α activity in posterior electrodes (*i.e.*, although, as in Newman et al. (2013), Boksem et al. did not test for the specificity of this increase in terms of spatial location); and *(ii)* a high subjective effort expenditure following the realization of the sustained attention task. Overall, these findings contribute towards disentangling the neural correlates of the sensory-motor deficiencies characterizing the attention decrement phenomenon. Further, in concert with these changes in pre-stimulus neural activity, TOT also affected the neural response of visual cortices, as discussed next.

4.3. Attention decrement as manifested in sensory VEP

4.3.1. P1 unaffected by attention decrement

According to Di Russo et al. (2008), the P1 represents the first processing stage of visual information following a stimulus presentation (occurred at 98 ± 11 ms post-stimulus in the present study), and reflects the conjoined engagement of two secondary visual cortical areas, namely the dorsal V3 and the ventral V4 (Di Russo et al., 2001, 2003; Mangun et al., 1997; Martinez et al., 1999). Our experimental design produced no effect of attention decrement on P1 features (*i.e.*, amplitude and latency).

As mentioned in the Chapter I (please see p. 59), the P1 enhancement represents a signature of focused attention, and has contributed to the development of the assumption that attention acts as a "*sensory gain mechanism*" (Hillyard et al., 1998). ERP results in this study and in previous studies (Boksem et al., 2005; Faber at al., 2012) demonstrate that P1 features are robust to the TOT effect. Yet, Weissman et al. (2006) found that momentary lapses in attention were associated with a decrease in the event-related hemodynamic response of the secondary visual areas, involving an alteration of the dorsal V3 and the ventral V4 activities. Taken together, these results suggest that the activity of visual secondary areas can be altered by attention decrement but such alterations may occur at a later processing stage, leaving the earliest stage unaffected.

4.3.2. N1p features affected by attention decrement

The N1p occurred at 157 ± 12 ms post-stimulus in the present study. This component reflects a reactivation of V3 areas (Di Russo et al., 2001, 2003; Mangun et al., 1997; Martinez et al., 1999) considered as resulting from a top-down modulation of visual cortices activity arising from the fronto-parietal network, and allowing for a deepening of information analysis (Di Russo et al., 2001, 2003). Our present results show that the N1p component was significantly affected by TOT effect, including a decrease in its amplitude and an increase in its latency.

While increases in N1p latency in response to the TOT effect have never been investigated to date, decreases in its amplitude have been reported previously in discrimination tasks (Boksem et al., 2005; Faber et al., 2012). First, the increase in N1p peak latency may be related to an increase in the computational burden of the fronto-parietal network with TOT. Indeed, as time elapses, the fronto-parietal network has to increasingly deal with a reorienting of attention from task-unrelated sources of information (*e.g.*, mind-wandering; Langner and Eickhoff, 2012) to the current task goals; as a consequence, it might take more time for these areas to trigger neural feedback signals to the secondary visual cortices, hence delaying their reactivation. Secondly, the decrease in N1p amplitude suggests a weakening of the sensory gain mechanism of attention with TOT. As previously mentioned, Weissman et al. (2006) reported a weakening of the event-related hemodynamic response of the secondary visual areas associated with momentary lapses in attention. The present finding of a reduction of N1p amplitude in association with unchanged P1 amplitude (see above), suggest that results by Weissman et al. (2006) might exclusively reflect an alteration of the late processing stage within the secondary visual areas. Given the poor temporal resolution of the hemodynamic response, such a conclusion could not be arrived at easily based on the results by Weissman et al. (2006). Finally, an alternative and complementary explanation is that both the increase in N1p latency and the decrease in N1p amplitude would result from the observed increased level of inhibition during the pre-stimulus period.

5. Conclusion

Overall, our study demonstrates the occurrence of an early increase in the pre-stimulus level of α-band power during sustained attention, preceding the degradation of behavioral performance characterizing attention decrement. This increase in α activity was specifically localized in a cluster covering the visual cortices as revealed by a Monte-Carlo permutation analyses. Further, the neural signatures of attention decrement also involve an alteration of the visual response of the sensory cortices as reflected by the N1p VEP component. The interpretation of an early inhibition of the visual cortices is in accordance with the mindlessness theory and with the observation that simple sustained attention tasks are subjectively perceived as quite difficult. According to the working hypotheses stated at the end of Chapter I, the early disengagement of the sensory cortices should be related to an over-engagement of a number of attention-related and motor cortical areas with TOT. This hypothesis is tested in the next chapter.

Chapter III

Adaptations of motor neural structures' activity to lapses in attention[69]

"*Swiftly the brain becomes an enchanted loom,*
where millions of flashing shuttles weave a
dissolving pattern — always a meaningful
pattern — though never an abiding one."

Charles Sherrington (1942)

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[69] **Published as**:
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Abstract

Sustained attention is fundamental for cognition and when impaired, impacts negatively on important contemporary living skills. Degradation in sustained attention is characterized by the TOT effect, which manifests as a gradual increase in RT. The TOT effect is accompanied by changes in relative brain activity patterns in attention-related areas, most noticeably in the PFC and the right parietal areas. However, activity changes in task-relevant motor structures have not been confirmed to date. This paper describes an investigation of such motor-related activity changes as measured with *(i)* the time course of CS excitability through single-pulse TMS; and *(ii)* the changes in activity of pre-motor (PMC), M1, PFC and right parietal areas by means of NIRS, during a sustained attention RT task exhibiting the TOT effect.

Our results corroborate established findings such as a significant increase ($p < .05$) in lateral prefrontal and right parietal areas activity after the emergence of the TOT effect but also reveal adaptations in the form of motor activity changes - in particular a significant increase in CS excitability ($p < .01$) and in M1 activity ($p < .05$).

1. Introduction

Sustained attention describes a fundamental aspect of cognitive processes vital for the successful execution of many activities of daily living, for example as in driving, or crossing a busy street. But attention resources are finite[70] and a gradual decrease in attention across time – the so-called TOT effect – usually arises from tasks requiring sustained attention. The TOT effect manifests behaviorally as an observable increase in RT over time and can therefore have serious consequences in terms of impaired performance in everyday tasks. For instance, attention deficits and fatigue have been linked with traffic accidents and work-related injuries (Czeisler et al., 2005). Other important areas where attention capacity has been identified as relevant include the clinical domain where patients suffering from ADHD, can see their goal-directed behaviors disrupted by attentional lapses (Reimer et al., 2005). Investigating the neural bases of sustained attention is key to a deeper understanding of this vital cognitive property.

As noted by Fox et al. (2005), during the performance of attention-demanding tasks, certain attention-related areas routinely exhibit increased activity (*e.g.*, LPFC and parts of the parietal cortex, Cabeza and Nyberg, 2000), whereas others demonstrate decreases in activity (*e.g.*, medial PFC, Gusnard and Raichle, 2001). Further, Fox et al. (2005) stressed that the more cognitively demanding the task, the higher the magnitude of these antagonistic patterns. In response to the TOT effect, marked increases (Paus et al., 1997; Fairclough et al., 2005; Yarkoni et al., 2009) and decreases (Paus et al., 1997; Coull et al., 1998; Lim et al., 2010) in activity are evident in attention-related cortical areas. In one particularly relevant study, Weissman et al. (2006) investigated the trial-by-trial relationship between fMRI-measured brain activity and RT and reported an increase in activity over the LPFC and parts of the right parietal area which was associated with the increase in RT. These authors concluded that the increase in activation observed after the occurrence of lapses in attention arose from increased demands on higher-order processing areas. The interpretation is that the longer attention is sustained, the higher the cognitive demand, and consequently the greater the activation in the LPFC and parts of the parietal cortex.

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[70] This section was written before I more deeply engaged myself in the analysis of the resources theory of attention decrement (see pp. 97-107) and this witnesses the evolution of my ideas during my PhD on a theoretical point of view.

It is worth highlighting that neural activity changes associated with the TOT effect occurrence do not appear to be limited to known attention-related areas. Based on the previously mentioned study by Weissman et al. (2006), albeit not highlighted by the authors, one can discern that the activity of the M1 contralateral to the limb involved in the RT also increases. However, apart from that study, no other research to date has focused explicitly on possible changes in the activity of motor structures once lapses in attention occur. This deficit impedes the creation of an integrated understanding of the adaptations of the nervous system to the TOT effect.

One means of investigating the activity of motor structures during RT tasks consists of using single-pulse TMS to probe the changes in CS excitability during movement preparation. During movement preparation, the CS excitability increases for the muscle group involved (Chen et al., 1998; MacMillan et al., 2004; Mars et al., 2007; Van Elswijk et al., 2007) and such neuronal activity changes characterize the motor preparation process (Rosenbaum, 1980). To the best of our knowledge, motor preparation has been only investigated during phasic alertness studies and the evolution of pre-movement neuronal activity accompanying the TOT effect remains unknown. The increased evoked response over M1 associated with the increase in RT found by Weissman et al. (2006) could be related to an increase in the pre-movement excitability of the motor structures.

As a contribution towards a better understanding of the neural adaptations to the TOT effect, the study described here investigated the time course of the activity of motor structures through two complementary experiments. In the first experiment, the dynamics of CS excitability was assessed through measurement at 5 min intervals during a sustained attention RT task of 30 min duration. Single-pulse TMS was applied during the ISI as subjects prepared for the ensuant stimulus. Through such an approach, we were able to focus on the neural correlates of motor preparation throughout the evolution of the TOT effect. In the second experiment, functional NIRS was exploited to investigate the time course of the changes in activity of the cortical motor areas, PFC and right parietal areas throughout the same sustained attention RT task. NIRS facilitates the investigation of cortical neural activity during hand movements in natural environmental settings which are comfortable and natural for subjects. This particular experiment allowed us to confirm previous results described in the literature regarding activity of attention-related areas as well as capturing any changes in the activity of relevant motor areas.

2. Materials and methods

Two series of experiments were conducted to assess *(i)* the CS excitability (*TMS experiment*) and *(ii)* the hemodynamic cortical changes (*NIRS experiment*) during 30 min of a sustained attention RT task. During both experiments, EMG recordings and neuromuscular tests (NMT) were identically carried out. The study was split into two experiments because of the difficulties in investigating CS excitability by TMS concurrently with NIRS, *e.g.* the placement of the NIRS optodes interferes physically with the placement of the coil necessitating an increase in the distance between the TMS coil and the scalp (*i.e.*, beyond 20 mm). As it has been shown that the magnetic field generated by a TMS coil dies off very rapidly as a function of distance (Bohning et al., 1997) such an instrumentation arrangement is not satisfactory. To compound the difficulties further it has been demonstrated that TMS can induce artifacts in NIRS measurements when performed over the same area (Näsi et al., 2011). The solution of two distinct experiments was therefore adopted to ensure independence of the TMS and NIRS measurements. The two experiments were conducted on two different groups of subjects to avoid the possibility of any task learning effects. Finally, a control experiment was performed on 4 subjects (recruited within the groups of the *TMS* and *NIRS experiment*) with single-pulse TMS and without a sustained attention RT task.

2.1. Participants

Fifteen right-handed male volunteers took part in the *TMS experiment* (aged 25.7±3.6 years; height 1.79±0.55 m; body weight 74.2±7.2 kg) and thirteen in the *NIRS experiment* (aged 29.0±6.6 years; height 1.69±0.34 m; body weight 80.6±3.4 kg). Student's t-test for groups performed on the age, height and body weight revealed no significant difference in these parameters between the groups of the *NIRS* and *TMS experiments* ($p = .36$; $p = .71$; $p = .33$; respectively). All subjects were right-handed according to the Edinburgh Questionnaire (Oldfield, 1971). No subject had any sign of neurological, respiratory, and cardiovascular disease or medication, which might affect brain and muscle functions. Neither had any subject epileptic antecedents which would have precluded the use of the TMS technique. Each subject provided written informed consent prior to participation in the study. All procedures were approved by the local ethics committee (CPP Sud-Méditerranée II, number 2010-11-05) and complied with the Declaration of Helsinki for human experimentation.

2.2. Experimental design

Both experiments were conducted in a quiet and dimly-lit room. Each subject performed the entire protocol once. The subjects were asked to sit at a table on which a stimulus light (white) source was positioned at a distance of 1 m from the subject's eyes (Figure 3.1). A computer screen was positioned just behind and above the light source to provide visual feedback of the force generated during certain phases of the protocol. The subjects wore a neck brace to reduce head movements and the head was fixed against a headrest by means of straps. The left forearm of each subject was rested upon the surface of the table. The dominant hand (*i.e.*, right hand for these subjects) was held in a neutral position in the sagittal plane and fixed with straps to prevent extraneous movements during contractions. The angle of the elbow was set to 110° (with 180° corresponding to full elbow extension). The thumb was fixed against a dynamometer allowing direct measurement of abduction force (Captels, Saint-Mathieu-de-Tréviers, France). The angles between the distal and the intermediate phalanx, and between the intermediate phalanx and the metacarpus were set to 180° and 70°, respectively. This thumb position allowed measurement of the highest EMG activity of the APB muscle in response to TMS and NMT. The arrangement is illustrated in Figure 3.1.

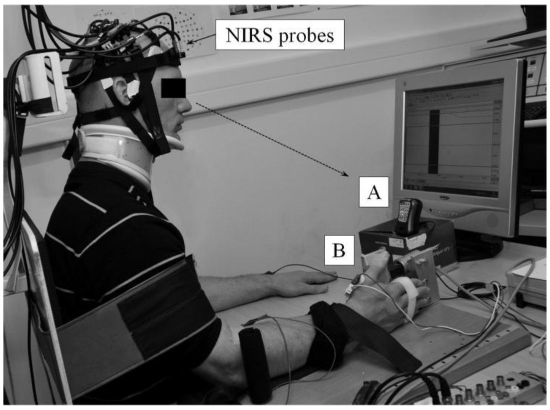

Figure 3.1: The experimental set-up during the NIRS experiment. A. Light source evoking the visual target stimuli during the sustained attention RT task. From the beginning of the task, subjects had to attend and prepare for the upcoming stimulus when the lighting source was off (*i.e.*, during ISIs). Subjects were instructed that when a flash occurred they should generate a thumb abduction as quickly as possible. **B. Dynamometer allowing the measurement of the thumb abduction movements** (*i.e.*, the motor responses). EMG electrodes can be distinguished on the belly of APB muscle. The screen positioned just behind the light source was turned off during the task and the resting state periods and turned on during the periods of the protocol requiring a visual feedback of the force production (*i.e.*, during the NMT and the warming up phase).

2.3. Experimental Protocol

First, a standard warm-up phase was performed consisting of 20 static submaximal contractions of the right APB (*i.e.*, through a thumb abduction task) in an intermittent mode. The level of force was maintained for 5 s followed by 5 s of recovery and was gradually increased after the 10th contraction. Visual feedback of the level of force generated was presented (a red trace) in real-time on the screen in front of the subjects (see Figure 3.1). Subjects were asked to match the red trace on the computer screen by modulating their motor activity. Then, the subjects produced three MVC of 5 s duration followed by 60 s of passive recovery. Afterwards, a simple visual RT task was performed of 1 min duration in order to familiarize the subjects with the paradigm. The task onset signal consisted of a 150 ms flash stimulus delivered using the light source (*i.e.*, photodiode arrays consisting of a few dozen emitters). A randomly varying ISI was set with a range of between 2 and 15 s. The motor response required of the subject was thumb abduction and this had to be performed as quickly as possible in response to the visual stimulus. In this sense, the task exploited in our protocol closely replicated the characteristics of the PVT developed by Dinges et al. (1997). We selected a simple RT task for three main reasons. First, simple RT tasks have been shown to be highly sensitive to changes in attention (Dinges et al., 1997; Lim et al., 2010). Second, during simple RT tasks, the stimulus saliency remains constant throughout the task. Therefore, the maintenance of optimal performance is mediated only through top-down processes without any stimulus-driven increase in the level of attention. Third, the absence of distracting stimuli allows the motor response to be fully prepared without the involvement of any inhibitory process (*i.e.*, in contrast to RT tasks which involve choice or recognition components). Consequently, the simple RT task exploited here allowed investigation of the neural substrates of the motor preparation process without any influence from the inhibition of inappropriate motor responses during the ISIs. The thumb abduction movement was chosen in this study as it facilitates easier EMG measurement over the APB muscle in response to single-pulse TMS (Chen *et al.*, 1998). This muscle, investigated during the *TMS experiment*, was also the main muscle involved in the motor response following the visual stimulus. Next, we determined the intensity of median nerve stimulation required to measure the maximal amplitude of the M-wave (I_M) and of the superimposed H-reflex (I_{Hsup}; for more details, see below) and began the NMT. This consisted of three single stimuli at I_M separated by 10 s intervals, and three single stimuli at I_{Hsup}. The contractions required to obtain the Hsup were performed at 10 % MVC and separated by 20 s intervals. The NMT time course is shown in Figure 3.2.A. and was realized before (pre-task NMT) and after (post-task NMT) the sustained attention RT task. Monitoring these neuromuscular variables (*i.e.*, H-reflex and M-wave) allowed us to assess whether or not the repetition of thumb abduction in the protocol induced fatigue at the spinal and muscle levels (Gandevia, 2001). Immediately after the experiment, the rating of perceived exertion (RPE) was evaluated by means of the Borg scale (from 6 to 20; Borg, 1970).

2.3.1. TMS experiment

After the pre-task NMT, a number of TMS pulses (in this case, four pulses) at a level of intensity that elicited the largest MEP amplitude and reproducibility (I_{MEP}; for more details describing how this level was determined, see below) were delivered at rest and also during voluntary contractions at 10 % MVC. Next, a sustained attention RT task of 32 min was performed with the same characteristics as the 1 min familiarization task. The average number of stimuli presented to the subjects over course of the task was 275 stimuli. Four TMS pulses at I_{MEP} were realized during the 2nd min (post 1) of the task and every 5 min thereafter (post 5, post 10, post 15, post 20, post 25, post 30) with variable inter-stimulation periods. The inter-TMS pulses intervals ranged from 5 to 15 s. The stimulation phases were delivered during the motor preparation period (*i.e.*, during ISIs), but never during motor execution. The task duration was set to 32 min in order to accommodate a measurement of CS excitability just beyond the 30 min period. Just after the RT task, TMS pulses at I_{MEP} were delivered both at rest and during voluntary contractions at 10 % MVC (post-task TMS). These post-task TMS pulses allowed us to investigate the changes in CS excitability once the RT task was complete. Specifically, we assumed that if the expected change in MEP amplitude occurred during the task, a return of this variable to the baseline (*i.e.*, pre-task) value following the task would definitively highlight a link between the act of performing the sustained attention task and the increase in MEP amplitude. It was followed by the post-task NMT, the production of one MVC, and the estimation of RPE. The NMT was performed in all subjects during the *TMS experiment*.

A control experiment was performed on 4 subjects to ensure that there was no effect from the repetition of TMS pulses on the MEP amplitude. It consisted of the delivery of 4 TMS pulses at I_{MEP} (equivalent to the pre-task TMS), followed by 4 TMS pulses 2 min later and every 5 min thereafter during the following 32 min (equivalent to the post 1, post 5, post 10, post 15, post 20, post 25 and post 30 TMS) and 4 TMS pulses just after 32 minutes (equivalent to the post-task TMS). During this control experiment, the subjects were instructed to sit relaxed, with neither visual stimulus presentation, nor motor responses required.

2.3.2. NIRS experiment

After the pre-task NMT, the subjects were instructed to rest for 2 min in order to stabilize the NIRS signals. This was followed by a sustained attention task of 32 min whose characteristics were the same as those during the 1 min familiarization task. After the sustained attention RT task, a 2 min resting period followed. This was in turn followed by the post-task NMT, the production of one MVC, and the estimation of RPE. The NMT were performed in 10 out of 13 subjects in the *NIRS experiment*. Over the course of the experiment, specific NIRS events markers were generated through the NIRS software (V6.0, Artinis, The Netherlands) in order to demarcate the periods of interest (*i.e.*, baseline and task). The time course of NIRS and TMS protocols are displayed in Figure 3.2.B.

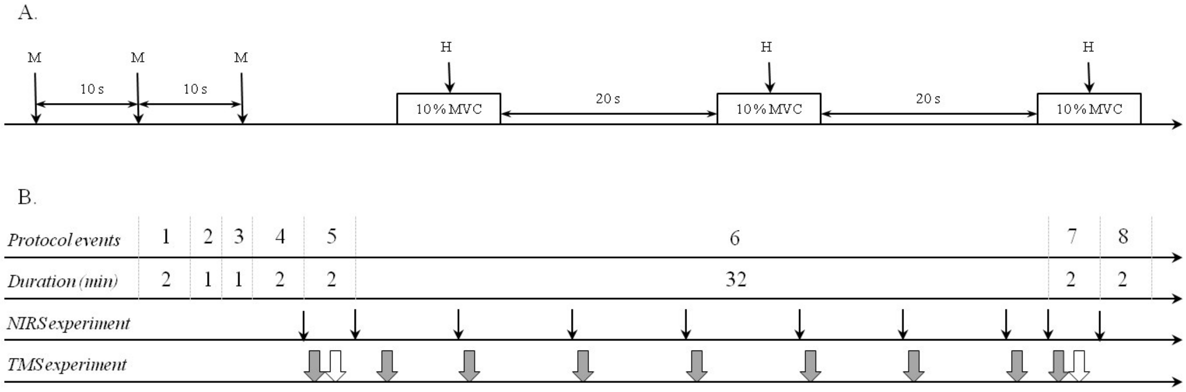

Figure 3.2: A. Neuromuscular tests (NMT). M and H represent the neural stimulation pulses performed at the intensity generating the M-wave and the superimposed H reflex responses, respectively. MVC = maximal voluntary contraction. **B. Time course of NIRS and TMS protocols.** Protocol events are: 1: Warming-up. 2: Resting period. 3: Familiarization through 1 min of sustained attention. 4: pre-task NMT. 5: *NIRS experiment* = pre-task resting period; *TMS experiment* = pre-task TMS. 6: Sustained attention task for 32 min. 7: *NIRS experiment* = post-task resting period; *TMS experiment* = post-task TMS. 8: post-task NMT. The thin black arrows in *NIRS experiments* represent the NIRS events, delineating the resting state periods and the task and each 5 min of the task. In *TMS experiment*, the thick gray arrows represent 4 TMS pulses without any contraction and the thick white arrows represent 4 TMS superimposed pulses (with voluntary contractions at 10 % MVC).

2.4. Measurements

2.4.1. Electromyographic recording

The EMG signals of the right APB muscle were recorded using bipolar, Ag/AgCl, square surface electrodes with a 9-mm diameter (Contrôle Graphique Médical, Brie-Compte-Robert, France). The skin was shaved, abraded and washed with emery paper and cleaned with 70° alcohol in order to obtain low impedance between the two bipolar electrodes (< 5 kΩ). The electrodes were positioned on the belly of APB muscle. The inter-electrode distance was 20 mm. The reference electrode was placed on the styloid process of the left ulna. The EMG cables were strapped to the table to prevent movement artifacts. The EMG signals were amplified (×1,000), digitized at 2,048 samples per second and synchronized with the force/motor responses and stimuli signals using the Biopac MP100 data acquisition system (Biopac System, Inc., Santa Barbara, CA).

2.4.2. Near-Infrared Spectroscopy recording

Functional NIRS is a versatile neuroimaging tool with an increasing acceptance in the neuroimaging-community (Cui et al., 2011; Derosiere et al., 2014a). Specifically, NIRS allows measurement in less constrained settings than those afforded by neuroimaging technologies such as MRI, for example in this case a sitting position, which is less susceptible to drowsiness than supine (Kräuchi et al., 1997). Further, NIRS allows subjects to perform tasks free from disturbance from scanner noise (in the case of MRI) and represents therefore a suitable technique for the investigation of focused attention. Functional NIRS utilizes, as fMRI, the tight coupling between neuronal activity and rCBF (Villringer and Dirnagl, 1995) to measure regional hemodynamic concentration changes in [O_2Hb] and [HHb] in the brain. By placing a pair of probes - consisting of an emitter of near-infrared light and a receptor - the relative local changes in the absorption and scattering of photons can be measured. These changes allow one to infer the relative local changes in hemoglobin state. Simulations have demonstrated (Hauessinger et al., 2011that the mean penetration depth of the photons for an interoptode distance of 3.5 cm in adults is 23.6 ± 0.7 mm and it follows a banana-shaped pathway. For more details about the basic principles of NIRS, please refer to the recent review of Ferrari and Quaresima (2012).

NIRS measurements were performed using a continuous wave (CW) multichannel system (Oxymon Mk III, Artinis, The Netherlands). The sampling rate was set to 10 samples per second. This particular device measured changes in optical density at two different wavelengths in the near-infrared range (nominal wavelengths 763 and 855 nm) and processed these to produce the corresponding changes in concentration levels of [O_2Hb] and [HHb]. A subject-specific differential pathlength factor (DPF) was used for this conversion based on the age of each subject (Duncan *et al.*, 1996) to yield more accurate measurement of the concentration changes in [O_2Hb] and [HHb] in terms of μM units (Delpy *et al.*, 1988). The inter-optode distance for each channel was set at 3.5 cm. Nine channels (each consisting of a two-wavelength source and detector) were used - three were positioned over the frontopolar part of the left, the right and the medial PFC (lPFC, rPFC and mPFC, respectively), one over the left PMC (lPMC), one over the left M1 area (lM1) and four over the right parietal area. The optodes were positioned according to the modified international EEG 10–10 system (American Electroencephalographic Society, 1994) and mounted on a custom-made cap fixed by several bands to the head of the subject. According to the EEG 10-10 system, the locations of the center of the channels over the lPFC, rPFC, mPFC, lPMC, lM1 corresponded to the Fp1, Fp2, Fpz, FC3 and C3 points, respectively. In separate independent studies (Muthalib et al., 2013, Anwar et al., 2013), we confirmed these NIRS channel positions as being over lM1, lPMC and PFC from activation maps of fMRI and using fiducial markers. The center of the 4 channels set in a square template over the right parietal area corresponded to the P6 point. During the placement of the probes, the Oxysoft software (V6.0, Artinis, The Netherlands) displayed real time measures of the signal quality for each NIRS channel based on the light source power level and the receiver gain. Once an acceptable signal-to-noise ratio was obtained, a zero baseline was set and the protocol executed.

2.4.3. Stimulation Recordings

2.4.3.1. Median nerve stimulation

Muscular and spinal excitability was evaluated by the M-wave and the superimposed H-reflex (Hsup), respectively. These potentials were obtained by stimulation of the median nerve by means of a high-voltage, constant-current stimulator (DS7AH, Digitimer Ltd., Hertfordshire, UK). Rectangular monophasic pulses of 500 µs were used. The cathode and the anode (Ag/AgCl electrodes) were placed over the pathway of the median nerve in the proximal and anterior part of the forearm. The first step consisted of the determination of the intensity of stimulation for each subject. To do so, we generated recruitment curves at the beginning of the experiment. We increased the current intensity by 5 mA increments every 10 s, to identify the individual stimulation intensity at which no further increase in the amplitude of the APB muscle potential (M-wave) was observed (I_M). Afterward, subjects were asked to perform a voluntary contraction at 10 % MVC, during which pulses at weaker intensity (*i.e.*, less than I_M) were delivered eliciting Hsup. The muscle contractions were separated by 20 s of passive recovery. Intensity was decreased by 5 mA, until the maximum amplitude of the Hsup (I_{Hsup}) was obtained.

2.4.3.2. Transcranial Magnetic Stimulation

Single TMS pulses of 1-ms duration were delivered using a Magstim 200 (Magstim, Whitland, UK) via a figure-of-eight coil (double 70 mm-diameter coil, maximum output intensity 2.2 T). The coil was positioned over the right-hand cortical representation of left motor cortex according to the C3 point of the 10-10 EEG system. The position was then adjusted in small amounts by moving the coil in the sagittal and coronal planes until the largest MEP was elicited in the right APB at 50 % of the maximal stimulator power output. The coil was held in position by straps surrounding a metallic spindle mounted on a mechanical arm with six degrees of freedom. Markers were positioned both on the subjects and the coil to precisely locate the position of the coil. An investigator remained during the experiment behind the subject to ensure that the coil did not move (as could be assessed via relative movement between the markers on the subject and the coil). To determine the TMS intensity of stimulation for each subject, individual recruitment curves were derived by gradually increasing the TMS intensity in steps of 10 % of the maximal stimulator power output. This process began at 50 % of the stimulator output and executed 4 stimulations per intensity with an ISI of 10 s, and finished at 100 % of the maximal stimulator power output. The stimulation intensity that elicited the largest MEP amplitude and reproducibility (I_{MEP}) was selected for subsequent measurement.

2.5. Data analysis

2.5.1. Reaction Time

The RT data was processed through the Acknowledge software associated with the Biopac system (Acknowledge 3.8.1, Biopac Systems, Santa Barbara, CA, USA). The RT was measured as the time between the flash stimulus (target stimulus) and the beginning of force production. The first 5 RTs of the task and the last 5 RTs of each block (1 block = 5 min) of the 32 min sustained attention task were then measured. Next, averages of the 5 RTs for each part of the protocol were obtained resulting in the mean RT at intervals corresponding to the 1st, 4th, 9th, 14th, 19th, 24th and 29th minute of the task. This avoids any confounding effect of the TMS pulses which took place at the beginning of the 2nd, 5th, 10th, 15th, 20th, 25th and the 30th minute of the task.

2.5.2. NMT

NMT data was also processed through the Acknowledge software. The peak-to-peak amplitudes of the M-wave and Hsup were calculated for each trial and then averaged for the pre and post-task NMT. The Hsup/M ratios were also calculated to ensure that there was no influence of peripheral changes on the spinal excitability parameters. During pre and post-task MVCs, the highest plateau of force in excess of 500 ms was considered as the maximal voluntary force.

2.5.3. TMS

The peak-to-peak amplitudes of the MEP at rest and during the sustained attention task were calculated for each TMS pulse. In order to prevent contamination of the MEP measurements by background EMG activity, trials with background EMG activity greater than 100 µV in the 200-ms window preceding the TMS artifact were excluded from the MEP analysis (Duque et al. 2009). The peak-to-peak amplitudes of the MEP were then averaged according to the protocol as follows: pre-task, 1 min, 5 min, 10 min, 15 min, 20 min, 25 min, 30 min and post-task. The percentages of the MEP amplitude during and after the task were calculated with reference to the pre-task MEP amplitude. The MEP/M and MEP/Hsup ratios were calculated with respect to the pre and post-task MEP to ensure that there was no influence of peripheral and spinal changes, respectively, on the central parameters. To do so, the pre and post-task NMT were used to normalize the pre and post task MEP, respectively. The peak-to-peak amplitude of the MEP was also calculated during the contractions at 10 % MVC and normalized on M (MEPsup/M) and Hsup (MEPsup/Hsup) amplitude at the same level of exerted force. The silent period (SP) duration was measured for pre and post-task TMS as the time between the pulse occurrence and the return of uninterrupted tonic EMG activity during the contractions at 10 % MVC. Similarly for the MEP amplitude, this calculation was realized for each TMS pulse and then averaged for pre and post task TMS.

2.5.4. NIRS

As is common for the modality (see Yamanaka et al., 2010), we focused on [O_2Hb] as the variable of interest to determine changes in cortical activity. Changes in [O_2Hb] have been recognized to better reflect cortical activation than [HHb] due to its superior contrast-to-noise ratio (Strangman et al., 2002). Dedicated NIRS software was used to analyze the [O_2Hb] signals acquired. The raw data were processed offline using the Oxysoft analysis program (V6.0, Artinis, The Netherlands) associated with the multichannel NIRS Oxymon Mk III system. The first step consisted of a preprocessing visual analysis as proposed in Minagawa-Kawai et al. (2011). The aim of this step is to remove channels where large movement artifacts had occurred or where signal-to-noise ratio was poor because of the presence of hair underneath the optodes. Then, the raw NIRS data were low-pass filtered using a cut-off frequency of 0.1 Hz in order to remove the heart rate and respiratory components (Huppert et al., 2009). From the resulting individual signals, the [O_2Hb] values were averaged over the 1st min of the pre-task baseline, the 2nd, 5th, 10th, 15th, 20th, 25th and the 30th minutes of the task. Then, the average of the 1st min of the pre-task baseline was subtracted from the averages of the other periods resulting in a differential in hemoglobin concentrations (Δ[O_2Hb]) at 1 min, 5 min, 10 min, 15 min, 20 min, 25 min and 30 min of task. These calculations were executed for the 9 channels. The changes in Δ[O_2Hb] for the four channels over the right parietal area were averaged together resulting in an overall right parietal response. The use of the average from these four channels was considered suitable given the lack of significant differences in Δ[O_2Hb] between these measurements over the right parietal area ($F(3, 18) = 0.19$, $p = .91$).

2.6. Statistical analysis

Statistica software (version 7.0, Statsoft, Oklahoma, United-States) was used for all analyses. All data were examined for normality and homogeneity of variance using Skewness, Kurtosis and Brown-Forsythe tests. A one-way repeated measure ANOVA was used to test for any significant effect of time (1 min, 9 min, 14 min, 19 min, 24 min and 29 min) on the changes in RT with a categorical factor (experiment, NIRS vs. TMS) to test for any divergence between the TOT effect on the RT during both experiments. Also, a one-way repeated measures ANOVA was used to test for any significant effect of time (1 min, 5 min, 10 min, 15 min, 20 min, 25 min and 30 min) on the changes in $\Delta[O_2Hb]$ over the lPFC, rPFC, mPFC, lPMC, lM1 and right parietal areas. When appropriate, the Fisher's LSD post-hoc test was used to detect paired differences. Due to multiple comparisons, we applied a strict 0.008 alpha level of significance (after Bonferroni correction) in the ANOVA performed on the NIRS data. Non-parametric Friedman ANOVA was performed to test for the significant effect of time (pre-task, 1 min, 5 min, 10 min, 15 min, 20 min, 25 min, 30 min and post-task) on the changes in MEP amplitude during the *TMS experiment*. The same Friedman ANOVA test was performed to test for the significant effect of time on the changes in MEP amplitude during the control experiment as well. When appropriate, the Conover's post-hoc test was used to detect paired differences. A Student's t-test was used for paired samples to test for pre-task to post-task differences in M, Hsup/M, MEPsup/M, MEP/M, MEPsup/Hsup, SP duration and MVC. A Student's t-test was also used for groups to compare the RPE measured after the NIRS and TMS experiments. The significance level was set at $p < .05$. Data are presented mean ± SD.

3. Results

3.1. RT and RPE data

As expected, the results did not show any significant difference between groups (*i.e.*, from NIRS and TMS experiments) with respect to the evolution of RT over time (F(6, 144) = 0.54, p = .77) and the time-on-task effect in both groups (F(6, 144) = 18.42, $p < .001$). The RT results demonstrate that the TOT effect occurred (according to significance measures) after 9 minutes over the sustained attention task. These results are presented in Figure 3.3. The t-test showed that the RPE values were not significantly different between the *NIRS* and *TMS experiments* (t = 0.25; p = .83). The RPE score after the *NIRS* and TMS *experiments* were 14.58 ± 1.73 and 13.71 ± 1.27, respectively.

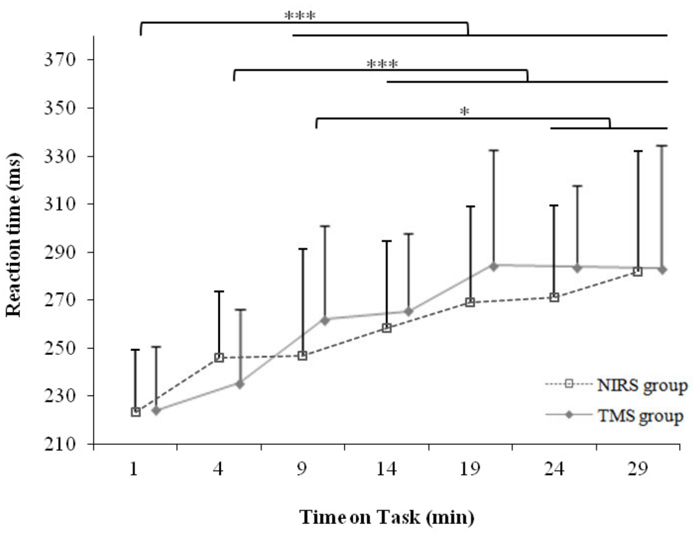

Figure 3.3: Evolution of reaction time over time during a sustained attention RT task of 30 min. Significant increase in RT occurred after 9 min of task compared to RT values of the first minute of task. *** p < .001. * p < .05. Vertical bars represent SD**.**

3.2. Pre and post-task NMT

The Student's t-test for paired samples showed no significant difference between pre- and post-task M-wave (t = 0.03, p = .98), Hsup/M (t = 0.79, p = .43) and MVC (t = 0.87, p = .39). All NMT results are presented in Table 1.

3.3. NIRS

All precautions were taken during the installation of the NIRS headset in order to pull hair away from the probes location. However, the data obtained from some subjects for the channels positioned over hair-covered areas showed a low signal to noise ratio because of the paucity of near-infrared light detected. Thus, 21.2 % of the NIRS signals were removed from the analysis.

A significant increase in $\Delta[O_2Hb]$ over time was observed over the lPFC (F(6, 72) = 5.89, $p < .001$), the rPFC (F(6, 72) = 2.99, $p < .01$), the lM1 (F(6, 48) = 3.35, $p < .05$) and the right parietal area (F(6, 36) = 9.15 , $p < .001$). A significant decrease in $\Delta[O_2Hb]$ over time was observed over the mPFC (F(6, 60) = 2.62, $p < .05$). No significant change in $\Delta[O_2Hb]$ was found over the lPMC (F(6, 54) = 1.35 , p = .25). Detailed post-hoc tests results of NIRS data are reported in Figure 3.4 (next page).

3.4. TMS

A significant increase in MEP amplitude was observed over time for the TMS group (F*r* (13, 8) = 38.31, $p < .001$) but not for the control subjects (F*r*(4, 8) = 5.33, p = .72). These results are presented in Figure 3.5. The Student's t-tests for paired samples showed no significant difference between the pre-task and the post-task in MEPsup/M (t = 0.58, p = .57), MEP/M (t = 0.64, p = .53), MEPsup/Hsup (t = 0,07, p = .95) and SP duration (t = 0.08, p = .93). These results are presented in Table 3.1.

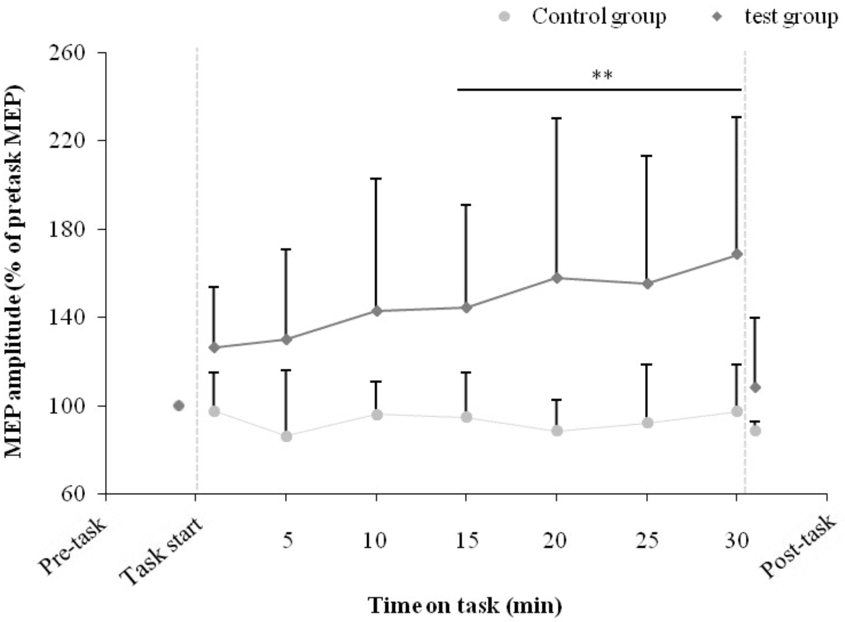

Figure 3.5: Evolution of the MEP amplitude over time during a sustained attention RT task of 30 min (experimental group) and at rest (control group). ** $p < .01$. Significant changes are the results of post-hoc tests and horizontal bars represent comparisons with pre- and post-task MEP amplitude values. Vertical gray dotted lines delimit the beginning and the end of the sustained attention RT task. Pre-task and post-task values were measured in the 2 min before, and in the 1 min after the task, respectively. It should be noted that post-task MEP values of the experimental group returned to the baseline level (*i.e.*, the pre-task values) and no significant difference was found between pre- and post-test MEP values ($p > .05$). This finding highlights a link between the act of sustaining attention and the rise in MEP amplitude. Vertical bars represent SD.

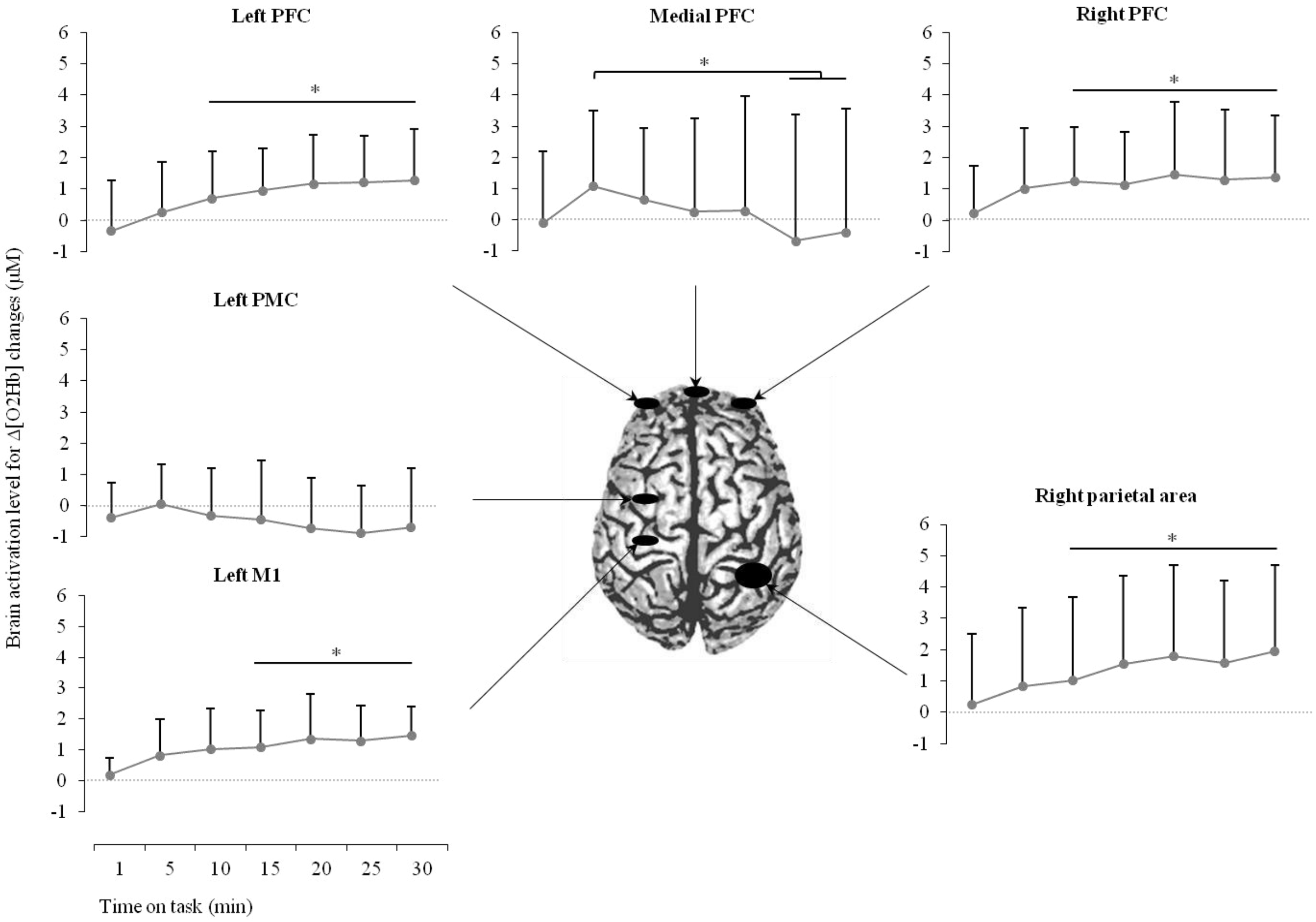

Figure 3.4: Evolution of NIRS signals over time during a sustained attention RT task of 30 min. * $p < .05$ after Bonferroni correction. Gray traces represent $\Delta[O_2Hb]$ changes. Significant changes are the results of post-hoc tests and horizontal bars represent comparisons with cortical activation after 1 min of task over the respective area (except for the mPFC where the significant changes are compared to the cortical activation after 5 min of task). Black circles represent the cortical areas investigated by the NIRS probes. Vertical bars represent SD.

Variables	Pre task	Post task	P - value
MVC (N) (n = 27)	73.79 ± 44.9	62.4 ± 38.1	p = .39
M amplitude (mV) (n = 22)	8.52 ± 3.29	8.49 ± 3.5	p = .98
Hsup/M (mV) (n = 19)	0.19 ± 0.09	0.22 ± 0.1	p = .43
MEPsup/M (mV) (n = 13)	0.65 ± 0.23	0.71 ± 0.29	p = .57
MEPsup/Hsup (mV) (n = 12)	3.61 ± 2.19	3.67 ± 2.03	p = .95
MEP/M (mV) (n = 13)	0.20 ± 0.15	0.24 ± 0.18	p = .53
SP duration (ms) (n = 13)	216.87 ± 41.29	218.3 ± 43.76	p = .93

Table 3.1: Comparison of pre- and post-task NMT and TMS variables. Results represent mean ± SD. The p-values are these of the t-tests.

4. Discussion

The aim of this study was to highlight how the activity of motor structures, in concert with attention-related cortical areas, adapts to the occurrence of the TOT effect. Our experimental design produced a TOT effect after, on average, 9 min of sustained attention as revealed by the significant increases in RT ($p < .001$). Our measurements and analysis demonstrate a significant increase ($p < .05$) in NIRS-measured LPFC (right and left) and right parietal areas activity concomitant with the emergence of the TOT effect. A significant increase in CS excitability ($p < .01$) and in M1 area activity ($p < .05$) were also found, occurring, on average, after 15 minutes of the task ($p < .05$). Finally, we have shown that after 25 minutes of the task, medial frontopolar PFC activity significantly decreased compared to its peak activation during the 5th minute of the task ($p < .05$). Before focusing on a discussion of these neural activity changes throughout the TOT effect development, we first discuss a number of relevant methodological considerations.

4.1. Methodological considerations

No significant difference was found between the groups with respect to the evolution of RT and the RPE estimation. Thus, the neurophysiological data (*i.e.*, NIRS and TMS data) measured in both independent groups are discussed together.

It should be noted that muscle fatigue did not occur as a result of the sustained attention RT task, a fact supported by the absence of any significant difference between post- and pre-task MVC values (Edwards, 1981). Also, the absence of change in *(i)* the SP duration and the MEP/Hsup, MEPsup/Hsup and MEP/M ratios, *(ii)* Hsup/M ratio and *(iii)* M-wave amplitudes reveal that the repetition of thumb abduction during the experiment did not induce fatigue at *(i)* supraspinal, *(ii)* spinal and *(iii)* muscle levels (Gandevia, 2001). This eliminates these potential confounding factors from subsequent interpretations.

Finally, it was important to rule out the possibility that the changes in CS excitability were related to the repetitive contractions of the target muscle over the duration of the RT task and consequently the post task TMS measurements (see Figure 3.5) were necessary to determine the nature of any such confounding influences. These TMS results demonstrate that in the 60 seconds following the task, CS excitability returned to a baseline level as measured during the pre-task resting period. This suggests that the changes in CS excitability are more plausibly explained in terms of arising as a result of changes in sustained attention during the experiment. Also, it is noteworthy that there was no significant increase in CS excitability in the control group (Figure 3.5), investigated with TMS but who were not required to perform RT. This result confirms that the increase in CS excitability measured over time in the group of the *TMS experiment* was isolated to the sustained attention RT task.

4.2. Increase in lateral prefrontal and right parietal areas activity after 10 min of task

The results indicate that the TOT effect emerges after 9 min of the task ($p < .001$) and interestingly, that LPFC and right parietal areas activities begin to significantly increase ($p < .05$) at around the same time (10 min of task). Some electrophysiological (Fairclough et al., 2005) and neuroimaging studies (Paus et al., 1997; Weissman et al., 2006; Yarkoni et al.,

2009) found similar results, with the time of occurrence of the reported increases in cortical activity and in RT depending on the cognitive load associated with the realized task. In particular the NIRS results presented here strongly corroborate the findings resulting from the trial-by-trial analysis performed by Weissman et al. (2006) and reinforce the previously mentioned interpretation of an increase in activation in response to increased attentional demand once the TOT effect occurs. According to Weissman et al. (2006), this increase in attentional demand follows - and is due to - the decrease in activity in sensory structures which usually accompanies the occurrence of the TOT effect (*e.g.*, Boksem et al., 2005). It is also worth considering the results reported here in terms of those from a recent study performed by De Joux et al. (2013) in which a decrease in left PFC oxygenation with the TOT effect occurrence was reported. The apparent conflict in terms of results should be considered in terms of differences of methods and instrumentation. For example, De Joux et al. (2013) do not report the location of their optical measurement channels, and may have investigated a different part of the left PFC area. Perhaps more significantly they exploited a discrimination task while we used a simple RT task (*i.e.*, a detection task) and differences in attention-related cortical activation have been previously identified between these both types of task (Langner and Eickhoff, 2012). Further investigation is required to better understand the role of the left PFC in discrimination versus detection tasks, especially in the context of attentional lapses.

In summary, our results demonstrate that activity in attention-related cortical areas increase in response to increased task demand across time, however the data also reveals that neural adaptations to the TOT effect occurrence involve additional cerebral structures which have not traditionally been associated with attentional effects.

4.3. Increase in cortico-spinal excitability and M1 activity after 15 min of task

The experiments also reveal significant increases in CS excitability and M1 activity after 15 minutes of the task ($p < .01$ and $p < .05$, respectively). This suggests that the CS tract and the M1 area are recruited in a complementary fashion with the attention-related areas in order to cope with the increasing task demand once the TOT effect occurs.

A number of previous studies have shown that shorter RTs, in contrast to longer RTs, were linked to *(i)* a larger increase in CS excitability during the movement preparation phase (Mars et al., 2007) and *(ii)* greater activity in the M1 area (Oguz et al., 2003). However, the present study suggests that such patterns do not manifest themselves in the same way in the context of the TOT effect. In fact the results here suggest that, despite the increase in CS excitability and M1 activity after 15 min, the RT continued to increase throughout the task (see Figure 3.3). While such results could appear surprising at first we interpret instead that the increase in CS excitability and M1 activity does not occur to counteract the TOT effect development. Rather, we suggest that the observed activity patterns demonstrate how other brain areas are engaged to cope with the increased task demand that follows the disengagement of sensory structures accompanying the TOT effect occurrence (Boksem et al., 2005; Weissman et al., 2006).

It is important to note that the increase in cortical activity was not ubiquitous in terms of the set of motor structures investigated. In particular, PMC activity did not significantly change over time. The stability of PMC activity has at least two implications. First, it highlights that the NIRS-measured increase in M1 activity is certainly not due to a global systemic response in [O_2Hb] over the motor cortical areas. Second, it suggests that the increase in CS excitability across time is not related to the activity of neural projections from the PMC which has direct access to the spinal cord (Dum and Strick, 2002). Therewith, we can infer that the increased CS excitability across time was related to increased activity of projections from the M1 area.

This suggests that the increase in MEP amplitude may be the product of an increase in cortical neurons excitability and/or in spinal neurons excitability (for review, see Reis et al., 2008). As the timing of increase in amplitude for both the MEP and the NIRS-measured Δ[O_2Hb] over the M1 area (*i.e.*, 15 min of task) are similar, one may suppose that the excitability was mainly increased at the cortical level. However, H-reflex results in humans (*e.g.*, Schiepatti, 1986) and intra-spinal neural recordings in monkeys (*e.g.*, Fetz et al., 2002) reported a facilitatory effect of motor preparation on spinal neurons activity. Further, it is notable that the NIRS-measured M1 activation resulted, in part, from the neuronal activation related to the execution of the motor response as well (*i.e.*, it did not arise only as a result of the motor preparation neural activity). The hypothesis that there is motor preparation-related changes in spinal excitability after 15 min of task (maybe in parallel to the increase in M1 area activity) cannot be totally excluded. Further investigations of the modulation of spinal excitability with the TOT are required to test this hypothesis. Because of differences in excitability of the motoneuron pools as regards the upper and the lower limbs (Espiritu et al., 2003) and in particular the significant difficulties in recording the H-reflex at rest over the upper limb, such measurements were not possible during our study. Our results present new questions regarding neural correlates of motor preparation in response to the occurrence of the TOT effect. For instance, investigating the possible changes ICF and ICI and the modulation of spinal excitability related to motor preparation throughout a sustained attention task would allow investigators to distinguish how the different parts of the CS tract adapt to lapses in attention.

4.4. Decrease in medial PFC activity after 25 min of task

The final noteworthy observation from the data was that after 25 min of the task, medial frontopolar PFC activity significantly decreased ($p < .05$) compared to its peak activation at a point 5 min into the task. Again, this result corroborates an increase in the task demand as the TOT effect emerges. Indeed, as mentioned in the introduction, Fox et al. (2005) described that the more cognitively demanding the task, the higher the magnitude of the attention-related decreases and increases in brain activity. The frontopolar part of the mPFC is known as one of the structures which reduces activity in response to attention-demanding tasks, as measured by means of fMRI (Gusnard and Raichle, 2001) and NIRS (Bauernfeind et al. 2011; Pfurstcheller et al., 2010). As a consequence, the potential increase in the task demand over time might be responsible for driving the decrease in mPFC activity.

One other (and complementary) potential interpretation involves a regional redistribution of cerebral blood volume (CBV) which would reflect both reduced mPFC activity and concomitant increases in actively participating brain areas. Indeed, while global CBV is constant due to autoregulation mechanisms (Lassen, 1964 ; Strandgaard and Paulson, 1984), it is well-known that CBV fluctuations happen regionally, as a function of local metabolic requirements. Lateral prefrontal, right parietal and M1 areas could belong to the regional areas requiring increased CBV with the TOT effect because of increased neural activity.

5. Conclusion

Overall, our study shows an increased involvement of key motor structures, including the CS tract and the M1 cortical area, in response to the TOT effect occurrence during a sustained attention RT task. As it has been previously proposed for some attention-related areas, we suggest that these motor structures undergo increased activation because they have to cope with the increasing task demand. We report that the increased CS excitability and M1 activity occurs significantly later than the increase in LPFC and the right parietal areas activity (for this task) which suggests that the motor structures are only recruited at a later stage of the process. To the best of our knowledge, this study is the first to approach the issue of the adaptations of the motor structures to lapses in attention. This work answers and opens new questions as regards the adaptation of motor structures' activity to the observed rise in RT over time, the so-called TOT effect.

Acknowledgments

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6. Supplementary materials

This short section reports supplementary behavioral results regarding the evolution of the number of omissions and commissions throughout TOT. Although these variables are of importance so as to characterize the attention decrement phenomenon, they have not been reported in the published version of the article because of their poor sensitivity to TOT in the task exploited in the present study. Further discussion on this aspect is provided below.

Using Matlab® (The MathWorks, Inc., Natick, MA, USA), the number of *(i)* omissions and *(ii)* commissions per 5-min duration block have been detected and computed as the percentages of *(i)* the total number of stimuli presented and *(ii)* the total number of motor responses realized during the 5-min duration block. Subsequently, Statistica software (version 7.0, Statsoft, Oklahoma, USA) was used for statistical analyses. The data were examined for normality and homogeneity of variance using Skewness, Kurtosis, and Brown-Forsythe tests. Because of the non-normal distribution of the samples, nonparametric Friedman ANOVAs were performed to test for the significant effect of TOT (*i.e.*, 0 to 5 min, 5 to 10 min, 10 to 15 min, 15 to 20 min, 20 to 25 min, 25 to 30 min) on omissions and commissions data. The significance level was set at $p < .05$. No significant effect of TOT was found, neither on omissions ($Fr = 4.6$; $p = .46$) nor on commissions data ($Fr = 4.9$; $p = .43$).

As discussed in Chapter II, Robertson et al. (1997) have pointed the finger at this kind of lack of sensitivity of certain sustained attention tasks to produce detrimental effects on specific components of behavioral performance. Further, this point has been introduced early in the present manuscript (see Chapter I, p. 96). In fact, according to the sustained attention literature, omissions are more likely to increase with high rates of stimulus presentation (*i.e.*, as exploited in Chapter II) and commissions are more likely to increase with TOT during Go-NoGo tasks (*e.g.*, the SART). However, we intentionally exploited low rate of stimulus presentation to be able to assess CS excitability in-between stimuli occurrence and we intentionally chose a simple visual RT task to allow the subjects to fully prepare their motor response and avoid any confounding factors in the interpretation of the expected changes in CS excitability that could have occurred if we had exploited a Go-NoGo task.

Chapter IV

Neural signatures of attention decrement: motor over-excitability, sensory inhibition

Intermediate reflection

"*It [Attention] implies withdrawal from some things in order to deal effectively with others and is a condition which has a real opposite in the confused, dazed, scatterbrained state [...].*"

William James (1890)

1. Introduction

This short chapter closes Part I of the present thesis (*i.e.*, which covered *Cognitive Neuroscience of attention decrement*) by briefly discussing the findings of the two studies presented in Chapter II and Chapter III. In summary, our investigation demonstrated that attention decrement was associated with *(i)* an early increase in the level of inhibition in the sensory cortices and *(ii)* a latter increase in M1 activity and CS excitability occurring in concert with *(iii)* an over-engagement of parts of the attention-related fronto-parietal cortices. To the best of our knowledge, our studies are the very first to explicitly address the question of the involvement of sensory and motor neural structures in attention decrement, and provide thus novel and interesting matter so as to better understanding the sensory-motor deficiencies characterizing the phenomenon.

2. Further discussion on the sensory-motor neural signatures of attention decrement

As James claims in the quotation noted on this Chapter's front page, attention involves a "*withdrawal from some things in order to deal effectively with others*". When he wrote that assumption in 1890, James specifically referred to the way focused attention attenuates certain perceptual stimulation and movement representation in order to deal more effectively with others at any given time. However, the assumption extends far beyond in terms of human cognition: it is indeed also true that any sensory information which is repeatedly presented to the human perceptual system and that proves to be irrelevant, is likely to be subjected to an active inhibitory mechanism occurring at the sensory neural level. The IOR is a compelling example of such a process. The results reported in Chapter II suggest that attention decrement is associated with a similar kind of inhibitory mechanism. This finding does not only afford explanation for the behavioral signatures of attention decrement - that is, decrease in perceptual sensitivity and increase in RT - but also provides data which can be used towards understanding a number of characteristics of attention decrement and sustained attention in humans. For instance, the finding of the involvement of an active inhibitory mechanism may explain why performing simple, repetitive tasks appears to be so cognitively challenging for humans. Another involvement of this finding is that it accounts for the re-orienting of attention to self-centered matters with TOT. In practical terms as well, these results have huge implications. For example, Robertson and O'Connell (2010) asked the question of "*Why do civil engineers build curves in highways across flat land where there is no geographical or geological need to do so?*". They suggest as an answer that drivers need complex visual stimulation in order to keep focusing on the road. Our results provide empirical support to this claim: changes in humans' environment may potentially reduce the IOR-like mechanism which negatively impacts focused attention by providing novel perceptual stimulation to the sensory nervous systems.

Of note, in the context of attention decrement, what is true at the sensory neural level is not necessarily true at the motor neural level (*i.e.*, contrary to focused attention which is expressed in similar way in the sensory and motor neural structures, see Chapter I, p. 71). We indeed demonstrated that attention decrement is associated with an over-excitability of CS neurons coding for the prepared movement and an increased activity in M1 area. This result sheds further light on the phenomenon by providing potential explanation of the causes of the increase in motor impulsivity often observed with TOT. Further, the bearing of this result is beyond the understanding of attention decrement but also extends on our knowledge of how focused attention works. Indeed, the finding that CS excitability and M1 activity increases with TOT also demonstrates that during simple sensory-motor tasks, while only one motor response is made possible and has to be prepared, the neurons coding for that motor response are not "fully" facilitated. That is, focused motor attention facilitates a given motor action, but not too much. The existence of such a restriction in neural facilitation has been demonstrated within sensory cortices as well, a finding which is further discussed in Chapter VIII (p. 238). At the motor level, this process could be at the very basis of behavioral flexibility, allowing us to more easily switch from one motor plan to another. If such an interpretation is valid, then it also signifies that, as attention decrement develops, humans become progressively less flexible in terms of action selection, the motor representation of the prepared action becoming over-facilitated over time. Also, if one considers the lateral inhibition interactions that underlies focused attention at the cortical and thalamic levels and that allow the suppression of unwanted movements (*e.g.*, see p. 90), then an increase in facilitation of the prepared motor action would result in a concomitant increase in the inhibition of unwanted actions, further reducing behavioral flexibility. All these different neurophysiological aspects are discussed in detail in Chapter VIII.

3. Taking advantage of changes in brain activity associated with attention decrement

Thus, it is likely that attention decrement could, in addition to its detrimental effect on perceptual sensitivity, RT and motor impulsivity, lead to a degradation in behavioral flexibility in terms of motor control. This point reminds us how much the phenomenon can negatively impact humans' daily living sensory-motor activities and, therefore, that there is a crucial need for developing means to reduce these negative impacts.

Of note, attention decrement was also, as expected, associated with changes in attention-related fronto-parietal areas' activity. While some fronto-parietal areas showed decreases in activity with TOT (*e.g.*, mPFC), a number of others became over-activated with TOT (*e.g.*, LPFCs and right parietal area). Such findings are fully in accordance with the interpretation of an increased cognitive effort to keep focusing on the task while time elapses. In this sense, the results presented in the current thesis are in accordance with the mindlessness theory of attention decrement, and are in opposition with the resources theory of attention decrement. Also, such as I argued regarding the increase in motor structures' activity with TOT, the finding of an increased activity of fronto-parietal areas demonstrates that these neural structures are not fully engaged at the very beginning of the focused attention task. Said another way, when one engages in a focused attention task, a "*cognitive reserve*" remains available.

That the attention decrement phenomenon is accompanied by such non-invasively measurable changes in attention-related cortices' activity can be taken as a real advantage from an engineering point of view: it may indeed provide relevant detectable signatures as inputs for cognitive-state tracking systems. This claim is especially true for the fronto-parietal cortices as it represents a supra-modal neural system, at the very basis of both focused motor attention and of focused sensory attention, independently of the movement to be executed and the sensory stimulation to be processed. One could suggest that it would be sensible to base a detection system on the increased level of α activity in visual cortices or even the increased left M1 activity so as to detect decrements in the level of attention but such neural signatures of attention decrement are task-dependent. For instance, in the case of auditory sustained attention, the level of α activity should rather increase within auditory cortices over time, and not over the visual cortices. This issue becomes even more complicated in the case of multi-modal sensory stimulation, which typically occurs in normal life. Also, in the case of focused attention to movements involving the left hand, the increase in motor cortices activity may certainly involve the right, and not the left, hemisphere. In this sense, tracking changes in activity of a supra-modal neural system such as the fronto-parietal network represents an alternative and potentially better way to detect attention decrements. The possibility of using such neural signatures to detect attention decrement is investigated in the second part of this thesis, which covers applications of attention decrement in Cognitive Engineering.

- PART II -

COGNITIVE ENGINEERING

Chapter V

Cognitive Engineering implications of attention decrement neuroscience

"*One man's 'magic' is another man's engineering.*"

Robert A. Heinlein (1973)

1. Cognitive Engineering: improving cognitive function through engineering approaches

During World War II, radar operators experienced more than anyone the behavioral deficiencies associated with attention decrement. The practical consequences were in some cases catastrophic and very quickly drew the attention of scientists as a phenomenon that demanded investigation (Lindsley and Anderson, 1944). Norman Mackworth did so, right away. That such interest in attention decrement emerged following such practical observations brings us back to the initial idea that it was important not only to better understand the phenomenon, but also to develop ideas with which we might either prevent its occurrence or compensate for its appearance especially in critical situations. Accordingly, investigating the neural correlates of attention decrement involves both a better understanding of the phenomenon (*i.e.*, through a Cognitive Neuroscience approach) and developing means to reduce the impact of its occurrence (*i.e.*, through a Cognitive Engineering approach).

People have always been aware of the need we appear to have for inventing new means to optimize our actions, perceptions and cognition in the physical world. For example, some evidence suggests that human factors' principles were adhered to in Ancient Greece[71] and some archeological studies depict that household tools were designed based on such principles in early Egyptian dynasties (Marmaras et al., 1999). Human factors and ergonomics however only exploded after the 1940s as a field of scientific investigation, mostly because of the huge technological advances that accompanied World War II and of their transfer to civilian applications. There was obviously a need to engineer systems facilitating human-machine interactions. Later on, in the 1980s (Card et al., 1983; Norman, 1983), cognitive engineering emerged as a natural transfer of what had been learned so far in cognitive psychology towards ergonomics[72] purposes (Lee and Kirlik, 2012). In the case of attention decrement, one of the goals that cognitive engineering pursues concerns the development of cognitive-state tracking systems (*e.g.*, Johnson et al., 2011). Cognitive-state tracking systems

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[71] Hippocrates described for example how a surgeon's workplace should be designed in order to facilitate its actions while operating.

[72] Human factors/ergonomics can be thus considered as involving physical ergonomics on the one hand, concerned with physiological and biomechanical characteristics of humans during physical activity, and cognitive engineering on the other hand, related to the cognitive aspects of human-computer interactions.

aim to capture relevant signatures of humans' cognitive state in order to provide them with some feedback or, in the case of adaptive automation (AA), so as to adapt a given device in real time. These signatures can be based on physiological (*e.g.*, skin conductance; Caffier et al., 2003) and/or physical (*e.g.*, blink duration; Bundele and Banerjee, 2009) variables of interest. It is worth remarking that one branch of cognitive engineering, neuroergonomics, is specifically devoted to the application of neuroscience towards ergonomics purposes. In this vein, neuroergonomics has recently led to investigations devoted to the development of particular cognitive-state tracking systems, which are based on the brain signatures of changes in cognitive state and called passive BCI[73].

On the whole, whatever the input exploited in these cognitive-state tracking systems in order to detect attention decrement (*i.e.*, skin conductance, blink duration or brain activity), the detection techniques are primarily based on pattern recognition and machine learning algorithms. Consequently, these methods are introduced next. I follow then with a brief description of the different physical and physiological markers that have been proposed so far in cognitive-state tracking systems and end this chapter with a description of the more recently proposed passive BCI concept and related novel possibilities offered by this field.

2. Data mining methods serving Cognitive Engineering

Data mining methods drive many applications which we encounter in daily life, extending for example from the prediction of our potential behaviors at the wheel by our car insurance company, to the optimization of websites based on our needs and preferences as an Internet user. Roughly, two main families of data mining methods can be described: clustering analyses (*i.e.*, also called *unsupervised classification analyses*) and supervised classification analyses. Clustering analyses allow us to define several clusters out of a single data set based on the similarity of the data points within each cluster and their dissimilarity across clusters

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[73] "Passive" BCI means that changes in cognitive state detected by the system does not result from the user's intention. This terminology is used in opposition to "active" BCI in which users try to control actively and voluntarily an electronic device.

(Jain et al., 1999)[74]. In this sense, clustering analyses can be considered as descriptive and exploratory (Rokach and Maimon, 2005; Veyssieres and Plant, 1998). For the purpose of detecting changes in attentional state during sustained attention, clustering analyses are inappropriate. In brief, applying clustering analyses in real time on NIRS data[75], for instance during a sustained attention task, would probably lead to the detection of several clusters but the interpretation of these different clusters would remain absolutely unknown. In other words, we should be able to detect changes in the behavior of NIRS data over time, but those changes could either represent a signature of attention decrement as sought, or something entirely different. Conversely, supervised classification analyses allow the prediction of the class to which a given input dataset belongs among several *labeled* classes. In the case of attention decrement for example, a binary supervised classifier would allow us to predict whether a given dataset (*e.g.*, a NIRS data sample) belongs to a "full attention capacities" class or to an "attention decrement" class. Given this, cognitive-state tracking systems are usually based on supervised classification analysis. Through a description of the basic principles of supervised classification analysis, this section points out how such a prediction of cognitive state could be feasibly achieved. This section does not intend to provide an exhaustive description of currently existing supervised classifiers but rather to offer enough background so as to establish acceptable understanding as to how cognitive-state tracking systems operate.

2.1. Basic principles of supervised classification analyses

The most important component of any supervised classification analysis is called *machine learning*. In this step, an algorithm basically "*learn*s" the respective features of two[76] (or *n*) subsets of data samples as obtained from the same data set. This data set is called the training data set as it allows us to train the algorithm to recognize patterns within the data. The main principle of supervised classification is that the classifier's user *a priori* knows, based on a "gold standard"[77], that subset A corresponds to label 1 while subset B corresponds

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[74] The measurement of similarity and dissimilarity between instances/objects/data points to be clustered constitutes a field of research by itself. For an interesting review, please refer to Jain et al. (1999).

[75] Or any other potential marker of humans' attentional state.

[76] For clarity purposes, I will take the example of a binary classifier, that is, discriminate between two classes.

[77] For example, in the case of attention decrement, the gold standard may be behavioral performance.

to label 2. The data samples from each subset are projected in what is called the feature space (*i.e.*, this step is also called step of quantification), which can be described as a z-dimensional space with each z_i being a given feature of the data. Based on this projection of the data samples from each subset within the same z-dimensional feature space, a decision boundary is produced. The decision boundary separates the projection of each subset of data samples (*i.e.*, which can be considered as two points clouds within the feature space) into two distinguishable classes. In the case of binary classifiers, the boundary decision is generally a discriminant function $f^*(x)$ (Duda et al., 2001). Based on this feature space, that is, once the classifier is trained, new data samples can be classified depending on what side of the decision boundary they are positioned in the feature space. This is the *testing* or *validation* step. These new data samples compose a data set which is different from the training data set and is called a test data set. The classification procedure is based on the following rule: if $f^*(x) > 0$ then the data sample associated with the feature vector x belongs to class 1 (*i.e.*, associated with label 1), otherwise the data sample is attributed to class 2 (*i.e.*, associated with label 2). Figure 5.1 provides an interesting example of the different steps of the classification procedure. In the next subsection, the main discriminant functions exploited in supervised classification analyses are described.

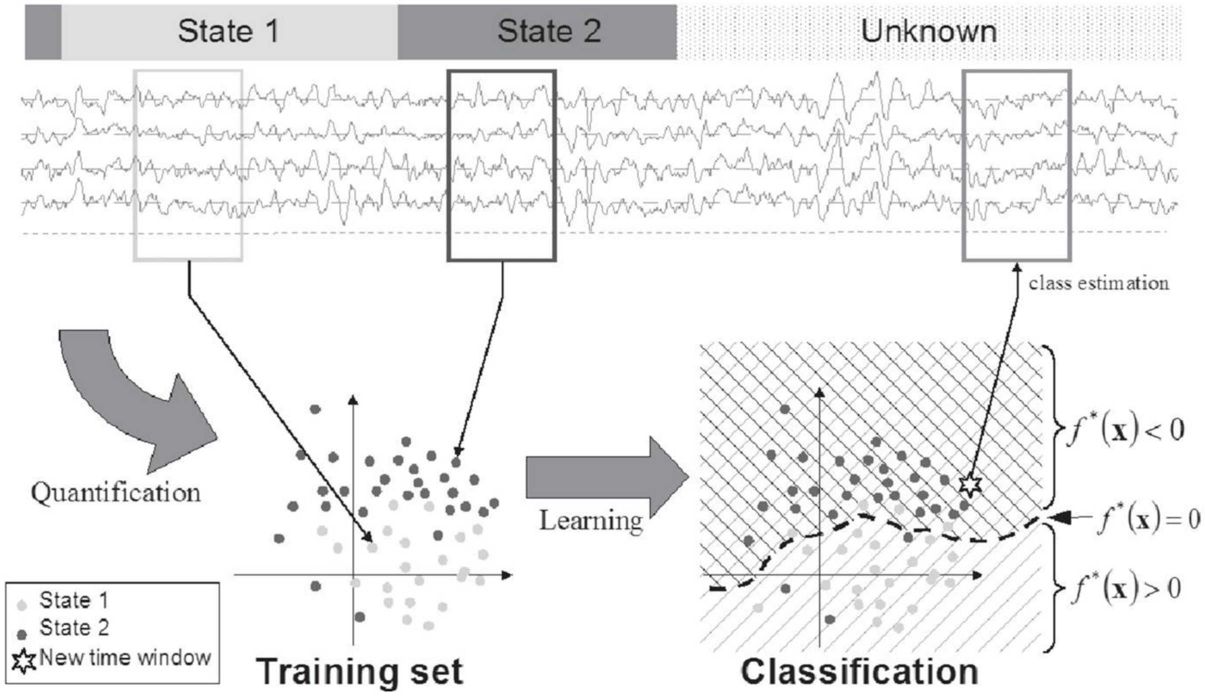

Figure 5.1: Basic principles of supervised classification analyses (after Besserve et al., 2007). *Top*: example of EEG recordings over four electrodes. *Top-left*: the classifier's user knows that two different states are present within the EEG data. For example, we can consider that state 1 represents the beginning of the task in a sustained attention task, then a "*full attention capacities*" state while state 2 may represent the end of the sustained attention task and then the "*attention decrement*" state. *Bottom-left*: based on this prior knowledge each data sample is projected in the feature space. In this two dimensional feature space, the features (*i.e.*, corresponding to the axes of the two-dimensional space) can be the power spectrum in α and in the θ bands for example. *Bottom-right*: a boundary decision (*i.e.*, a discriminant function $f^*(x)$ here) is fitted within the feature space in order to separate both point clouds. *Top-right*: new data samples are tested (*e.g.*, obtained from a new session of sustained attention). A class estimation is realized for each data samples, the algorithm predicts whether the subject is in a "*full attention capacities*" state or in an "*attention decrement*" state.

2.2. Main classification algorithms exploited in cognitive-state tracking systems

Overall, one may consider that the different classification algorithms differ from one another depending on two main characteristics. First, the discriminant function can be linear or non-linear. The second characteristic refers to how the discriminant function is generated: the discriminant function can result from a probabilistic model or can be directly based on the projection of the data samples as obtained from the training data set. In this subsection, three analyses are presented, which depict these two main characteristics of the classification algorithms: the Linear Discriminant Analysis (LDA), Support Vector Machine (SVM) and the K-Nearest Neighbors (k-NN)[78].

2.2.1. Linear Discriminant Analysis

Linear classification algorithms, as suggested by their name, are based on the adjustment of a linear function on the training data samples. This function can be written as $f(x) = wx + b$ where b is the bias and w is an orthogonal vector of the boundary decision $f(x) = 0$. LDA represents one of the approaches to adjust this function. LDA can be described as an adjustment of the function to the training data following a Gaussian probabilistic model allowing the determination of the most probable classes present in these data (Duda et al., 2001). Figure 5.2.A depicts the typical discriminant function as obtained with a LDA approach.

2.2.2. Support Vector Machine

In contrast to LDA which basically builds a probabilistic model of each of the classes based on every single data sample of the training data set, SVM algorithms attempt to minimize the separation error based on the points surrounding the decision boundary (Vapnik, 1998). It is worth noting that the discriminant function in SVMs can be either linear or non-linear. However, in the case of both cognitive-state tracking systems and active BCIs, linear SVMs are the most commonly exploited, probably because of their lower computational cost. For this reason, we will only consider linear SVM in this subsection. Thus, contrary to LDA, the data samples which are sufficiently far from the separating surface are ignored during the learning step. In the case of linear SVM, the discriminant function is of the same form as that of the LDA, that is, $f(x) = wx + b$, the only noticeable difference is that a margin surrounds this discriminant function. SVM algorithms aim at maximizing the width of this margin while keeping as many data samples as possible out of this margin. An example of a discriminant function obtained with a linear SVM is provided in Figure 5.2.B.

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[78] The information presented in this subsection can be found in a more detailed manner in Besserve et al. (2007). The aim of this subsection is to briefly describe and picture these three types of discriminant function.

2.2.3. K-Nearest Neighbors

K-Nearest Neighbors (k-NN) algorithms are quite different from the two preceding discriminant functions in the sense that there is no actual construction of a probabilistic model. Thus, in k-NN, there is no actual "training" needed since no model is built. In fact, k-NN is a method which is "data-driven" in some way, such that the class label of a given new data sample (*i.e.*, as obtained from the testing data set) corresponds to the predominant class label for the *k* nearest neighbors of that new data sample belonging to the training data set. As above-mentioned, no model is actually built but a metric is exploited in order to measure the similarity (or proximity) between data samples. Usually, the Euclidian distance is taken as a measure of similarity. Figure 5.2.C. depicts an example of a boundary decision as obtained with k-NN.

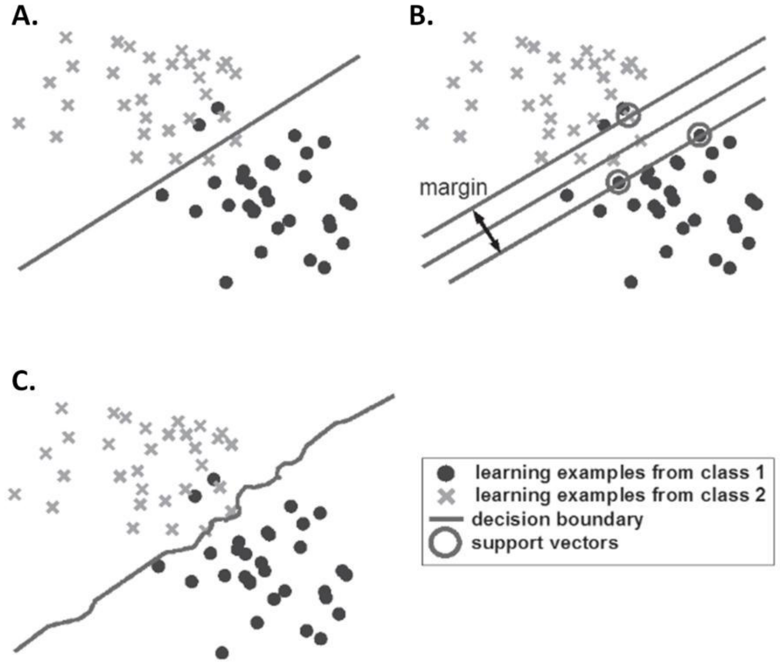

Figure 5.2: Examples of discriminant functions exploited in cognitive-state tracking systems and BCIs (after Besserve et al., 2007). A. Linear Discriminant Analysis (LDA). B. Support Vector Machine (SVM). C. K Nearest Neighbors (k-NN).

2.3. The problem of generalization

The "problem" of generalization refers to the capability of the model constructed based on the training data set to classify data samples from other data sets. Generalization is a significant issue to consider if one wants to evaluate the performance of a given classifier. A low capacity to generalize would be typically characterized by a high capacity to correctly classify samples from the training data set with a low capacity to correctly classify samples from a new data set. In this case, which is usually the consequence of what is called *over-training* (or *over-fitting*), the model fits too well to the training data samples and is subsequently less capable of correctly classifying different, new data samples. It is for this reason that, as I introduced earlier, the validation step must be realized on a different data set called the test data set: this procedure is called cross-validation. In order to realize the cross-validation procedure, the data initially recorded are usually split into two subsets composing the training and the test data sets. This partitioning is repetitively performed using different sampling based on all the samples of the initially recorded data and the classification accuracy is calculated for each partitioning. Two kinds of cross-validation can be distinguished: the k-fold cross-validation and the leave-one-out cross-validation (LOOCV). In the k-fold scheme, the training data samples are partitioned into two data subsets of the same size (*i.e.*, comprised of the same number of data samples). At each reiteration, one data sample is removed from each subset and injected in the other data subset (*i.e.*, in other words, two data samples are exchanged from one subset to another). In the LOOCV scheme, a subset of data samples is removed from the overall data set. At each iteration, a different subset of data samples is removed[79].

These cross-validation procedures lead to the calculation of different indicators of classification performance for each reiteration performed. For each indicator, the average of the values obtained at each reiteration is taken as the overall classifier performance. The main indicators of classification performance are described next.

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[79] Note that these cross-validation procedures strongly remind us what has been performed in Chapter 2 on EEG-measured alpha activity with the Monte-Carlo permutation analysis. This is because these procedures pertain to the same family of methods, typically based on re-sampling which can be used *(i)* in statistics, in order to estimate the precision of sample statistics (*e.g.*, as realized with bootstrapping or jackknifing methods); *(ii)* in statistics, in order to perform a significance test (*e.g.*, Monte-Carlo permutation analyses); and *(iii)* in supervised classification schemes, in order to validate a given model (*i.e.*, as described here).

2.4. Measures of classification performance

Several measures of classification performance can be described, the main of which are presented in Table 5.1.

		Condition as determined based on a « Gold Standard »		
		Positive	*Negative*	
Test outcome	*Positive*	True positives (TP)	False positives (FP)	***Positive predictive value*** = Σ TP / Σ outcome positive
	Negative	False negatives (FN)	True negatives (TN)	***Negative predictive value*** = Σ TN / Σ outcome negative
		Sensitivity = Σ TP / Σ condition positive	***Specificity*** = Σ TN / Σ condition negative	***Classification accuracy*** = (Σ TP + Σ TN) / Σ total samples

Table 5.1: Main measures of classification performance. The most common metrics in the case of cognitive state tracking systems are *sensitivity*, *specificity* and *classification accuracy*[80] (*e.g.*, Shen et al. 2008). In brief, sensitivity represents the capability of the classifier to classify actual positives as positives while specificity represents the capability of the classifier to classify actual negatives as negatives. Note that the positive predictive value is also called *precision*.

One other way to evaluate the classification performance is to calculate the area under the receiver operator characteristic (ROC) curve (Fawcett, 2006). The ROC curve depicts the evolution of the FP rate values as a function of the TP rate values for different thresholding of

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[80] This is worth mentioning that for a binary classifier, a classification accuracy of 50% represents the hazard level. For a three classes classifier, the hazard level is of 33%.

the discriminant function (Duda et al., 2001). In brief, for a given value of the discriminant function above the determined threshold, Class 1 will be predicted while for a given value beyond the determined threshold, Class 2 will be predicted. Given this, for an extreme value of the curve, data samples are attributed to Class 1 while for another extreme value, data samples are attributed to the Class 2 (Besserve et al., 2007). In brief, the main advantage of the area under the ROC curve is that it represents an overall indicator of the discriminative power of a given classifier, independently of the threshold selected. If the value of the area under the ROC curve reaches a value of 1, then it signifies that the discriminative power is maximal or, in other words, that the discrimination is perfect.

Based on such measures of classification performance, numerous studies have investigated the relevance of different markers (*e.g.*, physical, physiological or more specifically related to brain activity in the case of passive BCI) as inputs to cognitive-state tracking systems. These studies are described next.

3. Tracking human beings' cognitive state

What if my computer could adapt itself to my ever-changing cognitive state while I am writing my thesis? What if the brain activity of the neurosurgeon in the illustrative example given page 22 could be monitored during long-duration operations to provide him/her with some feedback about their cognitive state? What if the train accidents evoked by Ian Robertson (2003) could have been avoided? Developing means to achieve such objectives would prove to be extremely valuable. Cognitive-state tracking systems aim at doing this. Still, the advances regarding cognitive-state tracking systems are just burgeoning, and there are thus substantial avenues for future research in this branch of cognitive engineering (Zander et al., 2011). So far, researchers in the field have basically selected particular physical and physiological variables known to be related to humans' cognitive states, and have applied supervised classification analyses on these variables in order to investigate whether they could predict changes in humans' cognitive states with a high level of accuracy. Of note, the cognitive states that have been subjected to investigation were not limited to those associated with attention decrement but also included other aspects of cognition such as cognitive workload, the level of stress, or even aspects related to affective states regarding pleasure or frustration for example (Cutrell and Tan, 2008; Parasuraman, 2013). In the following two subsections, I specifically describe the different markers that have been proposed in the literature in order to detect changes in the level of attention during sustained attention tasks and then relate the potential of an emerging neuroimaging technique, namely NIRS, as a measurement modality for passive BCI.

3.1. Non brain-based cognitive-state tracking systems

Inferring a human's cognitive state does not necessarily require the direct monitoring of brain activity. Remarkably, passive BCI (*i.e.*, brain-based cognitive state tracking systems) have only recently become the subject of active investigation. In fact, a brief analysis of the history of research on cognitive-state tracking systems shows us that the initial aim of these systems (*i.e.*, as first proposed in the late 1990s; Galley et al., 1999; Singh and Papanikopoulos, 1999) was to detect extreme decrement in the level of alertness related to states of sleepiness and were thus, at first, exclusively based on physical markers such as eye blinks duration or head nodding. The predominant field of application of these investigation were as regards to the detection of pilots' or drivers' "*fatigue*".

The physical markers that have been investigated to detect these "*fatigue*" or sleepy states in drivers are based on head and facial movements, including head nodding, yawning, eye movements and blink rate and duration (Azim et al., 2009; Caffier et al., 2003; Eriksson and Papanikotopoulos, 1997; Galley et al., 1999; Gu and Ji, 2004; Horng et al., 2004; Ji et al., 2004; Jo et al., 2014; Khan and Mansoor, 2008; Perez et al., 2001; Popieul et al., 2003; Saradadevi and Bajaj, 2008; Singh and Papanikopoulos, 1999; Rogado et al., 2009; Smith et al., 2000; Wang et al., 2006). To capture these visual features, a camera is usually positioned in front of the driver, on the dashboard. Data mining methods are first applied to the recorded images so as to detect the face shape, the eyes and/or the mouth of the driver and then further supervised classification analyses are realized to classify whether the movement of the eyes and the mouth reflect an attentive or a sleepy state. Even if such systems could appear relatively elementary, their development has driven to a number of engineering issues regarding for example *(i)* the development of cameras which are not affected by changes in lighting (*e.g.*, in the case of night driving) or vibration conditions (Azim et al., 2009), *(ii)* the optimization of data mining algorithms to automatically detect the different components constituting the face (Gu and Ji, 2004), or *(iii)* the generalization of these classification algorithms to different skin colors, eyes colors, eyes shapes or genders (Khan and Mansoor, 2008). Overall, some studies have reported relatively good classification accuracy results, with up to 81 % of sensitivity and 86 % of specificity in the case of yawning detection (Saradadevi and Bajaj, 2008)[81] and up to 90 % of classification accuracy with respect to the detection of driver's sleeping episodes based on blinks duration (Khan and Mansoor, 2008). Also, as Eriksson and Papanikotopoulos (1997) noticed, the main advantage of such vision-based systems is their non-intrusiveness. However, these systems can only be applied in situations where bodily movements are restricted such as in transportation or in office environments and even in such environments, Azim et al. (2009) noticed that too large head movements (*e.g.*, rotations) can lead to failures of the supervised classifiers to detect the occurrence of sleepiness-related face movements. The use of psycho-physiological measurements may represent a viable complementary solution to resolve this issue.

The physiological markers that have been proposed to automatically detect sleepy states during driving[82] are related to the activity of the autonomic nervous system. It was for instance known since a long time that both the heart rate and the heart rate variability (HRV) vary as a function of the level of wakefulness (Egelund, 1982; Harris et al., 1972; Hartley and Arnold, 1994; Riemersma et al., 1977). Given this, cognitive engineers have recently applied supervised classification analyses based on these electrocardiogram features in the purpose of detecting the occurrence of sleepy states (Patel et al., 2011; Rogado et al., 2009; Sun et al., 2011; Viswanathan et al., 2011). By doing so, Patel et al. (2011) were able to detect sleepy states occurrence with up to 90 % classification accuracy in car drivers. Another marker of the activity of the autonomic nervous system that is known to vary as a function of the level of wakefulness is skin conductance (*i.e.*, also known as electro-dermal response or galvanic skin response). Here again, the relevance of this marker in order to predict drivers' cognitive states has been questioned. Bundele and Banerjee (2009) were able to predict whether skin conductance data were recorded before or after a long-distance driving (*i.e.*, of 550 km) with a sensitivity of 92.9 % and a specificity of 87 %.

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[81] In this study, yawning was the only feature considered as a marker of driver fatigue.

[82] The detection of drivers' sleepy states was indeed the preponderant application of these studies as well.

All in all, the results reported by these studies are encouraging for future development of cognitive-state tracking systems. However, the different physical and physiological inputs described in this subsection were exploited for the purpose of distinguishing attentive states from sleepy states. It seems sensible to assume that the level of attention may begin to decline long before falling asleep during sustained attention tasks, with potential dangerous consequences on humans' activities (Fu et al., 2008). Also, as a natural extension of the use of the above-mentioned (neuro)physiological markers as inputs for cognitive-state tracking systems, it has been suggested more recently to record brain activity so as to more directly infer the attentional state. Such brain-based cognitive-state tracking systems (or passive BCI) may offer a practical mean to detect decreases in the level of attention which are not necessarily associated with a state of sleep, and which could extend to other sensory-motor activities than driving.

3.2. Brain-based cognitive-state tracking systems or passive BCI

As Parasuraman (2013) highlighted, until the emergence of neuroergonomics in the 2000s, cognitive engineering investigation were mainly based on knowledge arising from cognitive psychology and little connection was made between cognitive engineering issues and knowledge about the brain. This deficit was probably related to the relatively influential philosophy of mind view (Dennett, 1991) in cognitive engineering which basically intimates that the neural structure and function are not directly relevant for understanding cognitive processes. The expansion of cognitive neuroscience in the 1990s (see Chapter I) and the related astonishing developments in the domain of neural engineering (*i.e.*, regarding neuroimaging technologies and signal processing) certainly contributed to the reversal of this view with a more brain-based approach of cognitive engineering, giving rise to neuroergonomics. The development of BCI is a great testament to this evolution as it depicts a clear application of knowledge about brain functioning towards neural engineering. Active BCIs are systems that allow the restoration of a channel of communication and control between the brain of a patient (*i.e.*, usually with reduced physical capacities) and an electronic device without involving any muscle contraction (Birbaumer, 2006). Such BCI are said to be active, given that the user actively/voluntarily attempts to control the given device. In contrast, the term passive BCI (or implicit BCI) has been suggested to depict any brain-based cognitive-state tracking systems that allows automatic adaptation of a system (*i.e.*, through AA or by providing some feedback to the user) based on the user's brain activity and related cognitive state, without his intention (Zander et al., 2010, 2011). In the case of the detection of changes in the attentional state, so far, the EEG has been the only technique subjected to investigation as an input in passive BCI.

3.2.1. Classifying the user's attentional state through EEG-based passive BCI

In the continuity of the works pursued on non-brain cognitive state tracking systems (see above), some investigation in the domain of EEG-based passive BCI aimed at discriminating attentive states from sleepy states (*e.g.*, Garces-Correa et al., 2010, 2014; King et al., 2005; Liu et al., 2013). In these investigations, EEG was recorded during a long-duration sustained attention task (*i.e.*, usually a driving task) which was known for inducing a state of sleep. EEG signals were then manually labeled and allocated to two subsets (*i.e.*, corresponding to the attentive and the sleepy states) exclusively based on the visual inspection by an "expert" of the EEG power spectrum features. A supervised classification procedure was then applied to the same data. Such approaches have yielded relatively good classification accuracy results such as for example by King et al. (2008 - sensitivity of 84 %, specificity of 82.1 % and accuracy of 83.1 %) or by Liu et al. (2013 - sensitivity of 86.5 %, specificity of 76.1 % and accuracy of 81.3 %). Thus, as physical and physiological markers, EEG seems to show promise for future development of cognitive-state tracking systems with the purpose of detecting sleepy states. However, such high levels of classification accuracy can be related to the fact that, here again, there is a substantial gap between an attentive (or even a wake) state and a sleepy state (Fu et al., 2008). So, can we bridge the gap? Or, in other words, is it possible, based on EEG signals, to distinguish changes in the attentional state which are not related to sleep?

To go farther in the field of EEG-based passive BCI, the first step has consisted of seeking observable changes in behavioral performance during sustained attention tasks in order to discriminate *two* different attentional states (*i.e.*, in other words, two levels of performance in an attentional task). It has long been known that sustained attention tasks are characterized by fluctuations in behavioral performance at both minute and multiple-minutes scales and that such fluctuations are accompanied by changes in the EEG power spectrum features (Makeig and Inlow, 1993). Following this observation, Trejo et al. (2006, 2007) investigated the possibility of discriminating a state of attention decrement compared to an attentive state in a three-hours duration MA task based on EEG power spectrum features. The authors labeled their EEG data on the basis of the changes in behavioral performance observed with TOT. The EEG data from the first fifteen minutes were considered as reflecting the *attentive state* while the EEG data from the last fifteen minutes were considered as reflecting the *attention decrement* state. Through such an approach, Trejo et al. (2006, 2007) reported a mean classification accuracy of 97.01 %. Stikic et al. (2011) went a step further and tried, meanwhile, to discriminate between two attentional states during a twenty-minutes duration choice RT task. These authors analyzed the moment-to-moment changes in behavioral performance reflected by a score taking into account the RT values and the percentages of correct responses. Above a certain threshold, this score was considered as characterizing an "acceptable performance level", characterizing a focused attention state. Below the same threshold, this score was considered as indicating an "unacceptable performance level"[83], or in other words, attentional lapses. The EEG power spectrum data were labeled on the basis of this threshold and supervised classification analyses was then performed. The performance reached a value of 81 % regarding sensitivity and nearly 90 % regarding specificity[84]. Overall, the above-mentioned investigations demonstrate the utility of using EEG-measured brain activity as an input to passive BCI in order to discriminate two different attentional states.

As a second step of progress, advances in the domain of EEG-based passive BCI has consisted of increasing the number of classes to be discriminated. Shen et al. (2008) continuously recorded EEG activity in ten subjects who underwent a twenty-five hour sleep deprivation experiment. Each hour, participants had to perform a three minutes duration auditory vigilance task (AVT; *i.e.*, an adaptation of the PVT described page 96). An AVT score was computed on the basis of the rate of correct responses and this allowed the researchers to distinguish five different levels of "*fatigue*" (*i.e.*, as induced by sleep deprivation), then exploited to label the EEG data. Using a multi-class SVM (*i.e.*, comprised of four classes), the authors were able to obtain a mean value of classification accuracy of

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[83] The threshold was first defined based on the scores obtained for a group of TSD participant (*i.e.*, who had not slept for 25 hours) as compared to a group of normally rested participants.

[84] The supervised classification analysis was actually performed for four blocks of five-minutes duration and classification accuracy varied depending on the block considered.

85.4 %. Although this study did not directly seek to classify different attentional states as obtained in a given sustained attention task, it does however provide a good illustration of the evolution of passive BCI towards multi-class systems.

In summary, the use of EEG as an input to cognitive-state tracking systems has now gone beyond the detection of sleep onset. Monitoring cortical activity seems to be a viable solution (not surprisingly) to classify changes in the attentional state during attention-related tasks. Also, research in the field of active BCI tells us that "*hybrid BCIs*, *composed of one BCI and another system (which might be another BCI) [...] achieve specific goals better than a conventional system*" (*i.e.*, than a simple BCI; Faress and Chau, 2013; Fazli et al., 2012; Leamy and Ward, 2010; Pfurtscheller et al., 2010). In the same vein, some researchers have recently proposed that the multimodal fusion of different markers of humans' cognitive states may allow a better classification performance than when each marker is exploited individually (*e.g.*, Lee and Chung, 2012; Rogado et al., 2009; Yang et al., 2010). Investigating the capability of novel markers to provide relevant information in order to predict humans' cognitive states may allow the addition of further, complementary inputs to such multimodal systems. NIRS-measured cortical activity represents one potential mean of creating such inputs.

3.2.2. Towards NIRS[85]-based (passive) BCI

The first demonstration of the potential of exploiting NIRS-measured cortical activity to classify different "cognitive states" in humans comes from the active BCI literature. For instance, Coyle et al. (2004, 2007) investigated the bilateral M1 activity by NIRS in subjects asked to imagine clenching the left or right hand and then exploited these brain signatures to test whether they could predict which hand was imagined being moved (*i.e.*, based on a supervised classification procedure). The aspiration of such investigations is to engineer devices that are controllable based on motor imagery. Coyle et al. (2004, 2007) reported an average classification accuracy of 80 %. Of note, contrary to EEG-based BCIs which usually involve a montage of 32 (or more) electrodes[86], the authors exploited a reduced number of

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[85] The basic principles of NIRS have been already introduced in the Material and Methods section of Chapter III and will therefore not be addressed in the present chapter. Moreover, a further description of the advantages of the NIRS technique in the context of (passive) BCI is provided in Chapter VI.

[86] For a related discussion, please see Müller-Putz et al. (2009).

NIRS probes (*i.e.*, two NIRS channels, one over the right, one over the left M1). Such a reduction in the number of sensors may represent a practical advantage in real-life settings, both for active and passive BCI. However, on the other hand, using a larger number of NIRS channels has proven to be relevant in active BCI, as it could provide additional relevant information. Indeed, based on a paradigm very similar to that of Coyle et al. (2004, 2007), Sitaram et al. (2007) were able to reach an average classification accuracy of 89 % using a 20-channels NIRS system arranged over the sensory-motor areas. This highlights one of the challenges of developing BCI or any cognitive-state tracking systems: respecting practical constraints while trying to obtain the highest classification accuracy possible. Overall, the few investigation that have been conducted on active BCI so far (*i.e.*, Bauernfeind et al., 2011; Coyle et al., 2004, 2007; Kanoh et al., 2009; Leamy and Ward, 2010; Sitaram et al., 2007) demonstrate the feasibility of using NIRS to predict humans' cognitive state.

In the context of passive BCI, investigations on the reliability of the NIRS technique for tracking changes in humans' cognitive state is only burgeoning. Most of those studies related to the classification of *affective states* (Girouard et al., 2013; Luu and Chau, 2009; Peck et al., 2013; Tai and Chau, 2009). For example, Luu and Chau (2009) tried to predict drink preferences of nine subjects based on NIRS-measured PFC activity. To do so, the authors first presented two different bottles to the subjects who had to answer whether they would prefer drinking one or the other beverage by clicking on a computer mouse. This allowed the authors to define which of the two drinks was preferred by each participant. Then, the same two stimuli were presented to the subjects alternatively and their PFC activity was recorded by means of NIRS. During this step no answer was required from the subjects. By applying a supervised classification analysis on the NIRS data, Luu and Chau (2009) were able to classify subjects' preferences with an average accuracy of 80 %. Similar findings have been reported elsewhere (Peck et al., 2013; Tai and Chau, 2009) and, overall, this demonstrates the potential for developing passive BCI based on NIRS inputs. The ambition of these systems is to automatically adapt, in real-time, computer interfaces and devices according to the preferences or the changes of the level of pleasure, anxiety and overall affective state of the user. The other branch of research on NIRS-based passive BCI focuses on the quantification of cognitive workload. This line of inquiry is closer to that of developing means to detect attention decrement since the idea is to avoid potentially dangerous states of "overload" that may be induced by tasks characterized by a high level of difficulty (*e.g.*, multi-tasking). In this vein, Coffey et al. (2012) recorded PFC activity in subjects that were performing n-back tasks with two different levels of difficulty[87]. Again based on supervised classification analyses and on the recorded NIRS data, the authors tested the possibility of predicting the level of cognitive workload that the subjects experienced. Coffey et al. (2012) were able to reach an average classification accuracy of 79.7 %.

In summary, both the investigations on passive and active BCI provide encouraging results regarding the use of NIRS as an input in cognitive-state tracking system. However, currently, there has been a clear lack of investigation on the potential of exploiting NIRS-measured cortical activity to detect attention decrement during sustained attention tasks. Thus, there is significant scope for further research in this field.

4. Cognitive Engineering applications of attention decrement: issues and objectives

4.1. Current issues

As introduced at the very beginning of this manuscript, attention decrement is behaviorally manifested by sensory-motor deficiencies, which may engender catastrophic consequences in real-life settings. Given this, the development of efficient cognitive-state tracking systems has become a topic subject to active research over the last fifteen years. Historically, the efforts have first been directed to the detection of sleepy states during driving, probably because of the huge socio-economic consequences that such situations can induce throughout the world (Johnson et al., 2011). Today, based on physical and physiological markers of the state of wakefulness, a given cognitive-state tracking system might be able to detect when a driver falls asleep with relatively good accuracy. Going a step

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[87] In this case, the assumption is that increasing the level of task difficulty leads to an increase in cognitive workload. This is however not always the case (see Chapter 1, pp. 108-109): a task characterized by a too low "level of difficulty" can be paradoxically perceived as strongly difficult and cognitively demanding. In these studies on cognitive workload, other variables are also investigated, including subjective expenditure for example, and allows the assessment of whether the different levels of task difficulty do induce a gradual increase in cognitive workload.

further, exploiting changes in cortical activity (*i.e.*, as measured with EEG) as an input to cognitive-state tracking systems has recently made possible the detection of more subtle changes in the attentional state as occurring during sustained attention tasks.

It is worth noting that the latest advances in the field have suggested that the combination of different measures through a multi-modal fusion approach may allow for an improvement of the classification accuracy performed by cognitive-state tracking systems. Investigating the relevance of novel markers of attention decrement as complementary inputs to cognitive-state tracking systems is in sympathy with this line of inquiry. In the context of active BCI and of affective and workload states detection, NIRS-measured cortical activity has been shown to allow high level classification accuracy (*e.g.*, Coyle et al., 2007; Luu and Chau, 2009; Coffey et al., 2012). However, in the context of attention decrement detection, NIRS-measured cortical activity has never been investigated to date and its utility in that regard was unknown until now.

4.2. Objectives of the current thesis

The brief literature review that has been established in the present chapter shows us that exploiting EEG-measured changes in cortical activity as an input to passive BCI has recently made possible the detection of changes in the attentional state occurring during sustained attention tasks. As part of the efforts for developing efficient cognitive-state tracking systems, the Cognitive Engineering part of this thesis aims at exploring the potential of NIRS-based cortical activity as an input suitable for a passive BCI design. With this aim in mind, a brief critical analysis of the literature is reported in **Chapter VI**, in which I point out the main strengths and weaknesses of the NIRS technique in the context of passive BCI. The second aim of the Cognitive Engineering part of this thesis is to test, based on supervised classification analyses, whether exploiting NIRS-measured attention-related areas' activity[88] for the purpose of detecting attention decrement could lead to good classification accuracy results (**Chapter VII**). Further, given that this study is pioneering in the field, there is a need for exploring which NIRS-based markers of attention decrement would provide the best input to cognitive-state tracking systems in terms of classification performance. Thus, the study

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[88] An explanation for the focus on these areas is provided in Chapter IV (p. 170).

reported in Chapter VII explores, through a data-driven approach, the sensitivity of the different NIRS variables (*i.e.*, [HHb] and [O_2Hb]) and of different attention-related cortical areas (*i.e.*, PFC and right parietal areas) to the detection of attention decrement.

Chapter VI

NIRS-measured prefrontal cortex activity in neuroergonomics: strengths and weaknesses[89]

> "*Our inventions are wont to be pretty toys which distract our attention from serious things. They are but improved means to an unimproved end, an end which it was already but too easy to arrive at.*"
>
> Henry David Thoreau (1904)

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Foreword: context of the present article

As a consequence of the increasing use of NIRS for functional neuroimaging, special issues on the technique came out in some neuroscience journals in the past months/years. Our team has contributed to these efforts through the publication of a research article within the motor control section of a special issue on *NIRS in Neuroscience* published in NeuroImage (Derosiere et al., 2014a[90]). The current chapter, meanwhile, is the result of an opinion paper that I wrote in response to a call for papers launched in the spring 2013 by the journal Frontiers in Human Neuroscience on the research topic: *NIRS in functional research of PFC*. This call for papers came out just at the right moment as I was at this time increasingly highlighting NIRS studies in neuroergonomics that, most of the time, exclusively focused on PFC. The issue was, to me, that by investigating PFC activity only, NIRS studies in neuroergonomics probably missed other relevant information conveyed by activity in other task-related cortical areas. This oversight could *(i)* impede the development of a comprehensive account of the cortical correlates of human-machine(s) interactions and *(ii)* decrease classification accuracy of any NIRS-based real-time classification of cognitive states. However, I reasoned, if neuroergonomics studies do so, there may be a compelling justification. These justifications are addressed in the first section of the current chapter. Then, I wondered, is NIRS-measured PFC activity sensitive enough for real-time classification of cognitive states? This question is addressed in the second section of the current chapter as well as in the next chapter (Chapter VII, pp. 204-226).

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[90] **Published as**:
Derosiere G, Alexandre F, Bourdillon N, Mandrick K, Ward T, Perrey S. (2014a). Similar scaling of contralateral and ipsilateral cortical responses during graded unimanual force generation. *NeuroImage. doi: 10.1016/j.neuroimage.2013.02.006.* The results of this study are not presented in this manuscript since it falls outside the scope of my PhD. However, the full version of this article is available in Appendix B.

1. Introduction

Contemporary daily life is more and more characterized by ubiquitous interaction with computational devices and systems and people are increasingly accustomed to - and dependent on - physical interactions in the digital domain. For example, it is commonplace for a person walking a busy street, to be engaged in conversation with a distant person using telephony, while simultaneously receiving directions via a GPS-enabled web application on their mobile device. This overwhelming increase in human-computer interactions has prompted the need for a better understanding of how brain activity is shaped by - and contributes to - performing sensorimotor actions in the physical world. In this context, neuroergonomics aims at bridging the gap between the abundant flow of information contained within a person's technological environment and related brain activity in order to adapt machine settings and facilitate optimal human-computer interactions (Parasuraman, 2013). One way to achieve this goal consists in developing adaptive systems. In neuroergonomics, AA relies on passive BCI capable of spotting brain signatures linked to the operator's cognitive state in order to adjust in real-time the operator's technological environment. With the growing area of interest in this topic, the need for neuroimaging methods properly suited to ecological experimental settings has risen. In this vein, NIRS presents some advantages as compared to other neuroimaging methods.

In this opinion article, we first concentrate on the benefits of utilizing NIRS for investigation in neuroergonomics. Recent neuroergonomics investigations have used NIRS recordings in a number of laboratories (*e.g.*, Ayaz et al., 2012; Li et al., 2009; Mandrick et al. 2013a, 2013b). It is particularly worth noting that most of these investigations have reported NIRS data from the PFC. We provide a brief review of these recent studies and their impact in the field by presenting a detailed analysis of the applicability of NIRS-measured PFC activity to discriminate cognitive states in real life environments. In this paper, we will address two main questions: are NIRS-derived hemodynamic variables sufficiently sensitive to changes in sustained attention when measured over the PFC area? Are these measures useful for delineating different levels of mental workload?

2. NIRS-measured prefrontal cortex activity in neuroergonomics: strengths

In 1977, Jöbsis published a paper in *Science* in which he proposed to exploit near-infrared light to investigate hemodynamic and oxygenation changes in the human brain – an event which gave rise to the field of NIRS-based functional monitoring of cortical activity. Since then, the technique has garnered immense interest across a multitude of fields of research in neuroscience including, recently, neuroergonomics. What makes this technique attractive for neuroergonomics investigators? The answer lies in a set of technical advantages offered by NIRS compared to other neuroimaging methods when performing experiments requiring ecological validity.

One such advantage is that subjects can engage in experimental tasks without the noise and movement limitation constraints associated for instance with fMRI investigations. In the same vein, the possibility of conducting experiments with the subjects in a sitting or standing position is a specific advantage of NIRS, since lying down - as it is required in the magnet - has been demonstrated to increase the risk of subject drowsiness (Kräuchi et al., 1997). The level of attention - a concept, as we will see below, of high interest in neuroergonomics - may be affected by this confounding factor when using MRI and it can be assumed that NIRS is a more appropriate method for the investigation of attention-related cortical activities (Derosiere et al., 2014b). In addition, the MRI environment severely limits the establishment of ecologically valid experimental conditions despite the efforts of simulation paradigms (*e.g.*, virtual reality) which have been proposed to solve this problem (Calhoun and Pearlson, 2012). Instead, NIRS or EEG may be exploited to counteract all these magnet-related issues. However, here again, NIRS presents some advantages over EEG. As stipulated by Di Nocera et al. (2007), although specific aspects of the EEG are sensitive to mental workload their robust acquisition and analysis in real-time is a problematic area. Also, unlike EEG, NIRS recordings are not affected by electrooculographic or facial EMG activity and environmental electrical noise - which are undoubtedly ubiquitous in human-computer interactions. Additionally, investigators having exploited both NIRS and EEG techniques may attest that the former technique is less sensitive to movement-related artifacts than the latter. NIRS signals are, however, not totally free of artifacts. Solovey et al. (2009) investigated the effect of physical behaviors inherent to computer usage (*e.g.*, mouse usage) during NIRS acquisition and proposed guidelines to further limit and correct artifact sources while using this modality in a neuroergonomics context. All the aforementioned technical advantages of NIRS are at the basis of its increasing use in neuroergonomics (*e.g.*, Ayaz et al., 2012; Li et al., 2009; Mandrick et al. 2013a, 2013b).

NIRS in neuroergonomics has been focused predominantly on one brain area of interest, the PFC. Focusing on a single specific cortical area stemmed from the goal of reducing the number of measurement channels required at the scalp level which is linked - in this field - to the aim of developing practical, ambulatory passive BCI. However, once this measurement simplicity is recognized, why should NIRS probes be placed over the PFC rather than, say, over parietal cortices? Firstly, the PFC is well-known as being involved in a large amount of cognitive and motor activities (Miller and Cohen, 2001) and is therefore a good candidate for the investigation of the interrelationships between cognition, action and the physical world. Secondly, there is an undeniable practical benefit of setting-up NIRS probes over this hairless scalp area as compared to other - more dorsal - scalp areas, since the presence of hair may impact on both photon absorption (Murkin and Arango, 2009) and the coupling of the probes with the underlying scalp.

The use of NIRS offers then, technical advantages in the field of neuroergonomics, and especially so, when probes are placed over the PFC - an area of interest when considering neuroergonomics issues. However, one could be skeptical regarding the focus on one particular area over others as it may reduce the amount of relevant information for quantifying the operator's cognitive state. This concern gives rise to the following question: does PFC activity measurement through NIRS-derived hemodynamic variables allow for quantifying the cognitive-states of the people/operator with sufficient sensitivity in real life environments?

3. Reliability of NIRS-measured prefrontal cortex activity for quantification of operator's cognitive-state

A primary issue in neuroergonomics concerns the assessment of mental workload. Mental workload reflects "*how hard the brain is working to meet task demands*" (Ayaz et al., 2012). Since excessive or insufficient mental workload can be associated with decreased efficiency and safety of human-computer interactions, mental workload has to be assessed for designing new systems or adapting them in real time. Based on NIRS-measured PFC activity, Ayaz et al. (2012) investigated the sensitivity of HbDiff - corresponding to the difference between [O_2Hb] and [HHb] values - for distinguishing three levels of mental workload during an Air Traffic Control task. In their study, augmenting the number of aircraft - 6, 12 or 18 - that the subjects had to manage in a given time resulted in three levels of difficulty. For each level, the changes (Δ) in PFC activity as the difference between HbDiff values measured at the end of the task and during the pre-task baseline were computed. The authors found significant increases in ΔHbDiff as a function of the level of difficulty. One of the conclusions drawn was that NIRS-based measurement of PFC activity appeared sensitive to large differences in task difficulty while sensitivity to smaller differences in task difficulty would have to be explored further using finer graduations in task level. However, the capacity of NIRS-based measurement of PFC activity to discriminate large differences in task difficulty has not been unequivocally proven and other published research suggests problems, especially for higher levels of mental workload. For instance, using a similar paradigm, Izzetoglu et al. (2004) showed that the ΔHbDiff measured over the PFC increased when considering conditions involving 6, 12 or 18 aircraft. Izzetoglu et al. (2004) however failed to find any increase in ΔHbDiff when the number of aircraft was increased to 24. In other words, ΔHbDiff clearly increased as a function of mental workload but plateaued thereafter. By manipulating the degree of difficulty (three levels) of a MA task, Mandrick et al. (2013b) provided further evidence of this finding. Subjective measures (*i.e.*, increase in the perceived difficulty and NASA-TLX scores) and behavioral results (*i.e.*, increase in RTs and rate of errors) confirmed that three distinguishable levels of workload were produced. However, Mandrick et al. (2013b) were only able to find differences in Δ[O_2Hb] between the "*easy*" and "*medium*" levels of difficulty. No difference in Δ[O_2Hb] was found between the "*medium*" and "*difficult*" levels of difficulty while Δ[HHb] was insensitive whatever the change in the level of workload. The authors computed linear regressions fitting for [O_2Hb] and [HHb] signals from the beginning to the end of the task and proposed to exploit the slope value of these regressions as an alternative index of the hemodynamic changes related to the task. By doing so, they could distinguish differences in [O_2Hb] patterns between the "*medium*" and "*difficult*" levels of difficulty. In summary, NIRS-measured PFC activity has been demonstrated to be able to distinguish between large changes in difficulty (Ayaz et al., 2012), especially for low to moderate levels of workload. At higher levels of workload, a plateau effect was found when exploiting Δ[O_2Hb], Δ[HHb] or ΔHbDiff suggesting that alternative data analyses should be exploited. The slope method for discriminating differences among mental workloads (Mandrick et al., 2013b) is one possibility to consider. Within active BCI systems - where subjects have to intentionally control external devices (Coyle et al., 2007) - the slope index has been identified as a discriminatory feature of the user's cognitive state (Faress and Chau, 2013; Power et al., 2011). Its application and implementation as passive BCI for quantifying the operator's mental workload constitute a future step in neuroergonomics.

Another area of research in neuroergonomics - closely related to mental workload - concerns the monitoring of sustained attention. In this case, the interest is to capture relevant brain signatures so as to detect performance breakdown - characterizing the so-called TOT effect - during sustained attention tasks. In this context, some NIRS-based PFC activity investigations revealed the sensitivity of the method to attention degradation. For instance, Li et al. (2009) showed significant changes in NIRS-measured [O_2Hb], total hemoglobin ([tHb]) and regional oxygen saturation (rSO_2) over the left PFC in parallel to TOT effect development during a prolonged driving task of 3 hours duration. In this study, no change in [HHb] accompanied the performance decline. In the same way, we recently demonstrated (Derosiere et al., 2014b) that the [O_2Hb] variable was sensitive to the TOT effect development[91] - in the form of increases over the lateral left and right PFC and decrease over the medial part of the PFC - during a simple RT task of 30 min duration. However, no significant change in [HHb] occurred in parallel to the performance decrement (personal data). When considered together, these results suggest that certain variables measured using NIRS over PFC may be sensitive to the TOT effect development. These variables include [O_2Hb] and [tHb], but not [HHb]. Of note, this concern may also be available for the mental workload discrimination since, as aforementioned, Mandrick et al. (2013b) were only able to distinguish differences between the "*medium*" and "*difficult*" levels of difficulty in their MA task when basing on the [O_2Hb] slope value, but not on the [HHb] slope value. Finally, the sensitivity of the rSO_2 variable to the TOT effect should be questioned since, in some cases, it has been found to remain stable despite performance degradation (De Joux et al., 2013; Helton et al., 2007). In these studies, the duration of sustained attention was shorter than in Li et al. (2009) and may explain the discrepancies in the results. To put it succinctly, the [O_2Hb] and [tHb] variables - as measured

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[91] We referred to the results of the study presented in chapter III, pp. 139-163, and published in *Cerebral Cortex* (Derosiere et al., 2014b).

over the PFC - can be considered sensitive to attention decrement regardless of task duration while rSO_2 may be sensitive to prolonged tasks only.

Finally it is worth noting that the scope of neuroergonomics is not limited to stressful conditions exclusively but includes positive mental states - such as pleasure - as well. In this vein, hedonomics is defined as "*that branch of science which facilitates the pleasant or enjoyable aspects of human-technology interaction*" (Hancock and Szalma, 2006). The aim - again tightly linked to mental workload issues - is to develop interfaces fostering the emergence of flow states (Csikszentmihalyi, 1990) in which operators are fully engaged in a task while information processing is fluid and almost automatic rather than effortful and controlled. As an example, NIRS-measured PFC activity has been recently exploited to investigate users' preferences within a BCI-based movie recommendation system (Peck et al., 2013). Briefly, the authors demonstrated that, based on changes in $\Delta[O_2Hb]$, users' movie preferences could be reliably classified. Such a result is encouraging and suggests that NIRS-measured PFC activity may allow for the adaptation of computer interfaces based on the operator's design preferences. However, to date, research on NIRS-based quantification of positive mental states still remains limited in neuroergonomics and further investigations are needed in this branch.

4. Conclusion and perspectives for NIRS in neuroergonomics

The investigation of cortical activity by NIRS presents real advantages especially when measurement in ecologically valid conditions is required. Further, the PFC is of interest for NIRS investigation in neuroergonomics - not only because of the measurement convenience that it offers - but also due to its acknowledged role in linking cognition, action and the physical world. Neuroergonomics studies have confirmed that NIRS-measured PFC activity can be useful for distinguishing changes in the operator's cognitive state. However, some NIRS-measured hemodynamic variables appeared relatively insensitive to certain changes in mental workload or attentional state. While alternative data analyses method can be proposed to solve some of these issues (*e.g.*, the slope method), further investigation is required to determine the relevancy of each NIRS-measured hemodynamic variable, as taken independently or in a combined manner, for distinguishing changes in the operator's cognitive-state.

Chapter VII

Towards a Near Infrared Spectroscopy-based estimation of operator attentional state[92]

"*When we can drain the Ocean into mill-ponds, and bottle up the Force of Gravity, to be sold by retail, in gas jars; then may we hope to comprehend the infinitudes of man's soul under formulas of Profit and Loss; and rule over this too, as over a patent engine, by checks, and valves, and balances.*"
Thomas Carlyle (1829)

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Foreword: context of the present study

As discussed in the previous chapter, NIRS-measured PFC activity could provide a sensitive marker as an input in passive BCI. However, the brief qualitative literature review realized in that chapter, though necessary, remains quite descriptive and to my knowledge, no direct investigation had been performed so far in order to quantitatively determine what level of accuracy could be provided by the different NIRS-measured hemodynamic variables in the purpose of detecting attention decrement (see also the brief literature review provided in Chapter VI, pp. 199-202). The study presented in the current chapter was devoted to do exactly this. Also, as I mentioned on page 196, by investigating PFC activity only, NIRS studies in neuroergonomics probably missed other relevant information conveyed by the activity of other task-related cortical areas. Thus, based on a data-driven approach, the present study also aimed at testing whether or not changes in the activity of the right parietal area could provide relevant information so as to detect attention decrement. These attention-related areas (*i.e.*, PFC and right parietal areas) have been selected in the present study because of their substantial role in sustained attention and because those are known to present changes in activity with attention decrement (please see Chapter III). Further, as mentioned on page 170, prefrontal and parietal cortices are known to be part of a supra-modal network (*i.e.*, a network involved independently of the stimulus modality), and are likely to be involved independently of the action to be realized. Given this, it is sensible to assume that PFC and right parietal cortices may allow the tracking of changes in the level attention in a wide range of sensory-motor activities.

Abstract

Given the critical risks to public health and safety that can involve lapses in attention (*e.g.*, through implication in workplace accidents), researchers have sought to develop cognitive-state tracking technologies, capable of alerting individuals engaged in cognitively demanding tasks of potentially dangerous decrements in their levels of attention. The purpose of the study reported here was to address this issue through an investigation of the reliability of optical measures of cortical correlates of attention in conjunction with machine learning techniques to distinguish between states of full attention and states characterized by reduced attention capacity during a sustained attention task.

Seven subjects[93] engaged in a sustained attention RT task of 30 minutes duration with NIRS monitoring over the prefrontal and the right parietal areas. NIRS signals from the first 10 minutes of the task were considered as characterizing the '*full attention*' class, while the NIRS signals from the last 10 minutes of the task were considered as characterizing the '*attention decrement*' class. A two-class SVM algorithm was exploited to distinguish between the two levels of attention using appropriate NIRS-derived signal features.

Attention decrement occurred during the task as revealed by the significant increase in RT in the last 10 compared to the first 10 minutes of the task ($p < .05$). The results demonstrate relatively good classification accuracy, ranging from 65 to 90 %. The highest classification accuracy results were obtained when exploiting the [O_2Hb] signals (*i.e.*, from 77 to 89 %, depending on the cortical area considered) rather than the [HHb] signals (*i.e.*, from 65 to 66 %). Moreover, the classification accuracy increased to approximately 90 % when using signals from the right parietal area rather than from the PFC. The results support the feasibility of developing cognitive tracking technologies using NIRS and machine learning techniques.

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[93] The NIRS data set exploited for this study is part of the set exploited in the study presented in Chapter III. Seven subjects were selected from the initial sample (n = 13) based on the signal-to-noise ratio obtained for every NIRS channels. This ratio was provided by the NIRS software (Oxysoft, V6.0, Artinis, The Netherlands) and was based on the light source power level and the receiver gain. Only data from the subjects that presented an adequate signal-to-noise ratio for ***every*** single NIRS channels were selected.

1. Introduction

Attention to a cognitively demanding task cannot be maintained at a high level indefinitely. During a sustained attention task, as time elapses, the level of attention progressively diminishes negatively impacting task performance (Weissman et al., 2006). Lapses in attention are behaviorally characterized by an increase in RT (*e.g.*, Lim et al., 2010) a phenomenon that can impact severely on activities of daily living. For instance, work-related injuries (Czeiler et al., 2005; Grandjean, 1979) and traffic accidents (Lal and Craig, 2001) are typical consequences of attention decrement. Recently, researchers have sought to develop cognitive tracking technologies capable of alerting users to such degradation in their attention levels (Johnson et al., 2011; Shen et al., 2008). The aspiration is that such technology can facilitate optimal human-machine interactions in real-life settings, both in the workplace and in the home.

While several indicators have been suggested for the detection of task-related changes in attention levels such as blink duration and rate (Caffier et al., 2003), HRV (Segerstrom and Nes, 2007) and EEG measures (Johnson et al., 2011) there is, however, no accepted “gold standard” technology for detecting attention decrement (Shen et al., 2008), aside from RT measures. Although some authors suggest that EEG-measured changes in brain activity might represent the most promising indicator of attention decrement (Lal and Craig, 2001), other studies have proposed that hybrid systems - based on the multimodal fusion of a number of indicators - may allow for more robust performance (Dong et al., 2011; Yang et al., 2010). In this vein, optical neuroimaging, namely NIRS, may represent a viable additional and complementary method for cognitive state monitoring. The purpose of this study is to address the issue by investigating the capability of this increasingly exploited neuroimaging method (*i.e.*, NIRS), to detect real-time changes in brain activity related to decrements in the level of attention during a sustained attention task. In particular, this study investigates the sensitivity of *(i)* different NIRS-measured hemodynamic variables as well as *(ii)* different attention-related cortical areas to the attention decrement phenomenon.

NIRS is a versatile neuroimaging tool increasingly adopted in the neuroimaging-community (Ferrari and Quaresima, 2012; Perrey, 2008). Ayaz et al. (2012) assert that "*NIRS is safe, highly portable, user-friendly and relatively inexpensive, with rapid application times* *and near-zero run-time costs*" (Bunce et al., 2006; Coyle et al., 2007; Izzetoglu et al., 2004; Strangman et al., 2002; Villringer and Chance, 1997). The modality has potential, as a portable measurement system for cognitive state monitoring outside the laboratory environment (Derosiere et al., 2014b; Parasuraman, 2013). Functional NIRS utilizes, as fMRI does, the tight coupling between neuronal activity and rCBF (Villringer and Dirnagl, 1995) to infer brain activation state from changes in [O_2Hb] and [HHb] concentrations characterizing the cortical hemodynamic response. Recently NIRS-derived cortical hemodynamic responses have been demonstrated to be sensitive to attention decrement during sustained attention tasks (Butti et al., 2006a, 2006b; DeJoux et al., 2013; Derosiere et al., 2014b; Helton et al., 2007; Li et al., 2009; Shaw et al., 2013; Warm et al., 2008). Further, it has been demonstrated through machine learning studies based on NIRS-measured hemodynamic variables (*i.e.*, [O_2Hb] and [HHb]) that the NIRS modality has some utility as a technology for active brain computer interfaces (*e.g.*, Power et al., 2011; Nambu et al., 2009; Cui et al., 2010; Sitaram et al., 2007; Naseer et al., 2013; Naseer and hong, 2013). Taken together, these findings suggest the potential of the technique as the measurement basis for an automated cognitive tracking technology. However, to date there have been no studies conducted to evaluate whether or not NIRS signals could be used for robust classification of different levels of attention during tasks requiring sustained attention. The primary object of past NIRS studies on sustained attention focused on better understanding the relationship between NIRS-measured cortical activity and degradation in behavioral performance. The current study aspires to go a step further by investigating the performance of a NIRS-based classification analysis aiming at distinguishing changes in the level of attention.

It is also worth noting that most of the aforementioned NIRS studies focused on one area of interest, the PFC (Butti et al., 2006a, 2006b; DeJoux et al., 2013; Helton et al., 2007; Li et al., 2009; Shaw et al., 2013; Warm et al., 2008). The PFC represents an appropriate candidate to investigate attention-related changes in brain activity since it has been described on numerous occasions as a cortical area significantly involved in human cognition (*e.g.*, Koechlin et al., 1999). There are also convenient, practical benefits to mounting NIRS probes on this scalp area. One such benefit is that compared to other, more dorsal areas, the scalp in this region is hairless. Hair presents a well-known problem in NIRS as it can impact dramatically on both photon absorption and the coupling of the probes with the underlying scalp (Murkin and Arango, 2009). The associated optical losses can severely degrade the signal-to-noise ratio reducing the reliable interpretability of the signal. Another important benefit of PFC-oriented measurement is that by focusing on a single specific cortical area, the measurement setup is consistent with the aim of developing practical, ambulatory cognitive-state tracking technologies since it allows for a reduction in the number of measurement channels required at the scalp level. However, by investigating PFC activity only, NIRS studies in the field may miss other relevant information conveyed, potentially, by activity in other task-relevant cortical areas. Excluding information from such areas could limit the potential classification accuracy of NIRS-based classification of cognitive states. It is then crucial to investigate the potential of other attention-related areas' activity, as measured through NIRS, to better capture the attention decrement. Lesion studies in patients (Posner and Rafal, 1987) as well as neuroimaging studies in healthy subjects (Coull, 1998; Fink et al., 1997; Pardo et al., 1991) suggest a significant role for the right parietal area in sustained attention processes and changes in activity under this area has been suggested as involved in attention changes (Derosiere et al., 2014b; Coull et al., 1998; Paus et al., 1997). This cortical region represents then another potential candidate for the discrimination of changes in the level of attention. Testing this hypothesis is an important aspect of the research described here.

Selecting the most discriminative variable(s)/feature(s) is an important aspect of any machine-learning problem (Shen et al., 2008). Given that none of the aforementioned sustained attention studies performed any NIRS-based classification analysis, there are currently no guidelines concerning which NIRS variables to focus on in order to detect as accurately as possible any decrement in the level of attention. While some previous studies demonstrated that the [HHb] variable was insensitive to time-on-task during a sustained attention task (*e.g.*, Li et al., 2009), others have described significant changes in both the [HHb] and [O_2Hb] variables throughout sustained attention tasks (Butti et al., 2006a, 2006b; Fallgatter and Strik, 1997). In the study described here, we hope to shed light on these discrepancies by investigating classification performance based on the [O_2Hb] variable, the [HHb] variable and a combination of both.

In summary, as part of efforts to develop effective cognitive-state tracking technologies, this paper reports on a study investigating the potential of detecting attention decrements during a sustained attention task through optical measurement of related brain activity. Beyond this primary investigation, we also seek to test the hypotheses that *(i)* in addition to the PFC, other attention-related areas (*i.e.*, the right parietal area) may facilitate the detection of attention decrement with good accuracy and *(ii)* exploiting both NIRS variable(s) (*i.e.*, [O_2Hb] and [HHb]) is valuable in improving performance for such efforts.

2. Materials and Methods

2.1. Participants

Seven male volunteers took part in this classification study (aged 29.0 ± 6.6 years). All subjects were right-handed according to the Edinburgh Questionnaire (Oldfield, 1971). None of the subjects reported that they suffered from neurological, respiratory, and cardiovascular disease or medication, which might affect brain perfusion and function. All procedures were approved by the local Institutional Review Board for the Protection of Human Subjects (CPP Sud-Méditerranée II, number 2010-11-05) and complied with the Declaration of Helsinki for human experimentations. Each subject provided written informed consent prior to participation.

2.2. Experimental set-up

Experiments were conducted in a quiet and dimly lit room. Each subject performed the entire protocol once. The subjects were seated at a table on which a stimulus light (white) source was positioned level with the eyes at a distance of 1 m. The left forearm of each subject was rested upon the surface of the table. The dominant hand (*i.e.*, right hand) was held in a neutral position in the sagittal plane. The angle of the elbow was set to 110° (with 180° corresponding to full elbow extension). The thumb was fixed against a dynamometer allowing direct measurement of abduction force (Captels, Saint-Mathieu-de-Tréviers, France).

2.3. Experimental Protocol

First, a standard warm-up phase was performed consisting of twenty static submaximal contractions of the APB (*i.e.*, through a thumb abduction task) in an intermittent mode. The level of force was maintained for five seconds followed by five seconds of recovery and was gradually increased after the tenth contraction. Visual feedback of the level of force generated was given in real-time on a computer screen positioned in front of the subjects. Once the warm-up phase was realized, the computer screen was turned off and a simple visual RT task was performed over the course of one minute in order to familiarize the subjects with the paradigm. The task onset signal consisted of a flash (150 ms duration) delivered using the light source (*i.e.*, photodiode arrays consisting of a few dozen emitters). A randomly varying ISI was set with a range of between two and fifteen seconds. The motor response requested from the subject was a thumb abduction task to be performed as quickly as possible in response to the visual stimulus. In this sense, the task exploited in our protocol closely replicated the characteristics of the PVT developed by Dinges et al. (1997). Such a simple RT task has been shown to be highly sensitive to changes in attention (Lim et al., 2010; Dinges et al., 1997). Further, during simple RT tasks, the stimulus saliency remains constant throughout the task and the maintenance of optimal performance is therefore only mediated through top-down processes without any stimulus-driven increase in the level of attention. Following the familiarization RT task, the subjects were instructed to rest for two minutes in order to produce a reference resting state in the NIRS signals. This was followed by a sustained attention task of thirty minutes whose characteristics were the same as those during the one minute familiarization task. Over the course of the experiment, event labels were set using the NIRS acquisition software (V6.0, Artinis, The Netherlands) in order to demarcate the periods of interest (*i.e.*, baseline and task). Immediately after the experiment, the RPE was evaluated by means of the Borg scale (from 6 to 20; Borg, 1970). The time course of the experimental protocol is presented in Figure 7.1.A (please see next page).

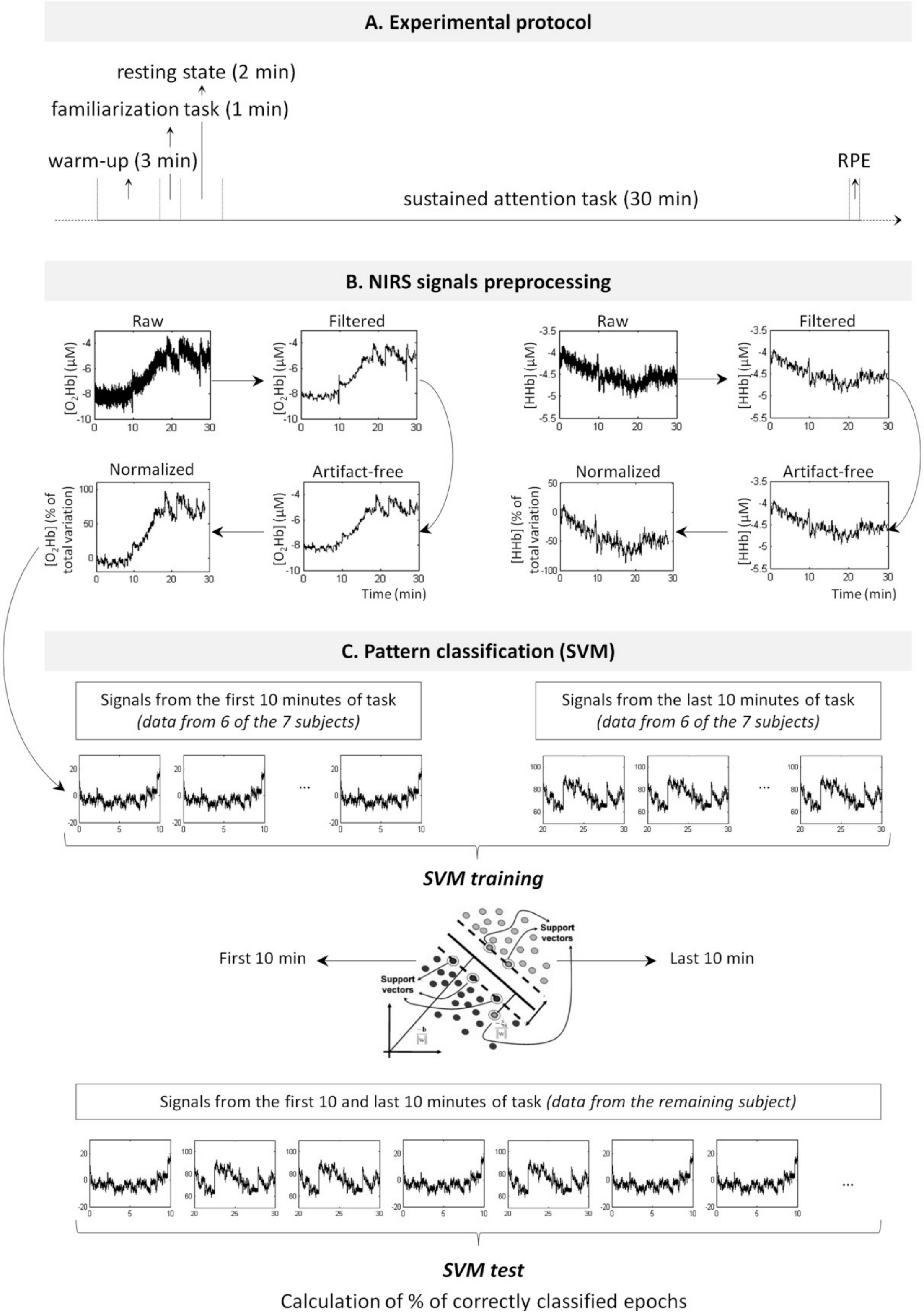

Figure 7.1: Illustration of the experimental protocol and analysis procedure. A. Time course of the experimental protocol. RPE: Rate of Perceived Exertion. **B. NIRS signals preprocessing steps.** *Left*: [O_2Hb] signals. *Right*: [HHb] signals. C. **NIRS signals classification based on SVM.** *From top to bottom*: Filtered, artifact-free, normalized signals are first exploited in the SVM learning step using six of the seven subjects. A model is built, represented here by its feature space. Finally, a SVM test is performed using the signals of the single remaining subject and the percentage of correctly classified epochs is computed. See Methods for further details.

2.4. Measurements

2.4.1. Reaction time

The force/motor responses and stimuli signals were synchronized and digitized at 2,048 samples per second using the Biopac MP100 data acquisition system (Biopac System, Inc., Santa Barbara, CA).

2.4.2. Near-Infrared Spectroscopy

The NIRS technique has been described elsewhere (Perrey, 2008). NIRS measurements were performed using a CW multichannel NIRS system (Oxymon Mark III, Artinis, The Netherlands). The data acquisition sampling rate was set to 10 Hz. This system allows measurement of changes in optical density at two different wavelengths in the near-infrared range (nominal wavelengths 763 and 855 nm) before converting these into changes in concentration levels of [O_2Hb] and [HHb]. A subject-specific DPF was used for this conversion based on the age of each subject (Duncan et al., 1996) and this allowed measurement of the concentration changes of [O_2Hb] and [HHb] in μM (Delpy et al., 1988). The emitter-detector distance was set to 3.5 cm. In the present study, the measurements were performed using seven channels over the regions of interest. Three were positioned over the frontopolar part of the lPFC, rPFC and mPFC, and four over the right parietal area. The probes were placed according to the modified international EEG 10–10 system (American Electroencephalography Society, 1994) and mounted on a custom-made cap fixated by several bands surrounding the head of the subject. According to the EEG 10-10 system, the locations of the centers of the channels over the lPFC, rPFC and mPFC corresponded to the Fp1, Fp2 and Fpz points, respectively. The centers of the 4 channels set in a square template over the right parietal area corresponded to the P6 point. A representation of the channel locations can be seen in Figure 7.2. During the probe placement, the Oxysoft software (V6.0, Artinis, The Netherlands) allowed real time assessment of the quality of the NIRS signals for each of the seven channels based on the light source power level and the receiver gain. Once an acceptable signal-to-noise ratio was obtained according to the signal quality assessment, a zero baseline was set and the protocol was executed.

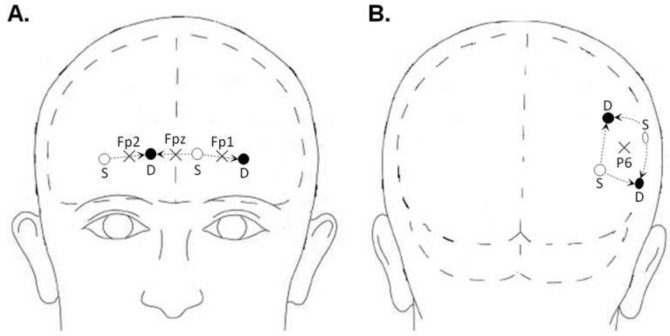

Figure 7.2: Placement of NIRS probes showing frontal (A) and dorsal (B) views. Crosses represent locations from the EEG 10-10 system. Empty circles - noted "*S*" - represent sources and black circles - noted "*D*" - represent detector probes.

2.5. Data analyses

2.5.1. Behavioral data

The RT data was processed through the Acknowledge software associated with the Biopac system (Acknowledge 3.8.1, Biopac Systems, Santa Barbara, CA, USA). The RT was measured as the time between the flash stimulus (target stimulus) and the beginning of force production. Responses were considered correct if the dynamometer was engaged between 150 and 600 ms after stimulus onset. All other responses were considered incorrect. Such a cut-off time window has been exploited in other RT studies (*e.g.*, Faber et al., 2012) and facilitates the exclusion of outlying RT values in the dataset. We calculated RTs of the first ten and last ten minutes of the task and then computed averages of the RTs obtained for these two periods.

2.5.2. Near-Infrared Spectroscopy

2.5.2.1. Signal preprocessing

The [O_2Hb] and [HHb] signals acquired from the NIRS instrumentation were initially filtered using a fourth order digital low-pass Butterworth filter with a cut-off frequency of 0.1 Hz in order to remove the heart rate and respiratory components (Huppert et al., 2009). Next, movement artifacts were removed on specific, visually identified channels by using moving SD and spline interpolation routines in Matlab (Mathworks, Natick, MA). This method has been validated using simulated, as well as real NIRS signals and has been shown to improve the detection of evoked hemodynamic responses (see Scholkman et al., 2010, for details). Finally, given that the datasets contained information regarding cortical hemodynamic changes over several regions of the brains and from many different subjects, a z-normalization of the signals was performed. From the resulting signals, a supervised classification procedure was performed by means of a linear SVM algorithm.

2.5.2.2. NIRS data classification using support vector machines

SVM can be considered as one of the most powerful classification algorithms as it is able to learn linear decision boundaries as well as more complex ones with relatively low complexity and few user-defined hyper parameters (Burges, 1998). Nonlinear decision boundaries are learned using the “kernel-trick” which consists of mapping the data into a higher-dimensional space using a kernel function and finding a linear separation in that space. An example of kernel function is the Radial Basis Function (RBF) defined as follows:

$$K(x, y) = \exp\left(\frac{-||x-y||^2}{2\sigma^2}\right)$$

Where x and y are two data points and σ is the width of the RBF.

In the current study, we used a linear SVM (*i.e.*, using linear kernel) as the decision boundary between the two brain states (*i.e.*, full attention vs. attention decrement) appeared to be sufficiently linear. The linear SVM has already been used in previous studies on attention decrement detection based on EEG signals, illustrating high classification accuracy results (*e.g.*, Shen et al., 2008). Like other linear classifiers (*e.g.*, LDA), a linear SVM uses a hyperplane to separate data points from each class. Additionally, the linear SVM chooses the hyperplane with the maximal distance from the nearest training points. This distance is called the "margin" and the nearest training points to the optimal hyperplane are called "support vectors". Figure 7.1.C. shows an illustrative example of an optimal hyper-plane as constructed by a linear SVM. Margin maximization increases generalization ability of the classification algorithm. However, such a learning scheme is sensitive to outliers and overtraining. For this reason, a regularization parameter C is used to reduce data over-fitting. Depending on C, the optimal margin will either expand or diminish and more or less points will subsequently become support vectors, respectively (Burges, 1998; Cortes and Vapnik, 1995). In the current study, we used the default value of 1 for the regularization parameter C with the software Weka (version 3.6.8, University of Waikato Hamilton, New Zealand). We designed the SVM for two-class classification (*i.e.*, full attention versus attention decrement). The NIRS signals from the first ten minutes of the task were considered as characterizing the '*full attention*' class, while the NIRS signals from the last ten minutes of the task were considered as characterizing the '*attention decrement*' class (this assumption was then supported by analyzing the RT values as described below; see RT results, Figure 7.3). Classification analyses were performed over data segmented and averaged over one second duration epochs. Thus, for each subject, six hundred time points were obtained for each class (*i.e.*, sixty seconds × ten minutes) and constituted the corresponding point clouds within the feature space. The signal feature selected was the magnitude (*i.e.*, averaged for each one second duration epoch) of concentration values (in μM) of the considered NIRS variable(s): [O_2Hb], [HHb] or both [O_2Hb] and [HHb]. Also, classification was based on the NIRS signals from *(i)* the PFC area exclusively, *(ii)* the right parietal area exclusively and *(iii)* both the PFC and the right parietal areas. These distinct feature vectors allowed us to investigate classification accuracy over a range of NIRS variables and cortical area(s). By doing so, the resultant feature pool was comprised of between three (*i.e.*, using [O_2Hb] or [HHb] from the three channels over the PFC) and fourteen features (*i.e.*, using both [O_2Hb] and [HHb] from the seven recorded channels). Data obtained from six of the seven subjects were exploited as the training set. Once the training step was realized, each class of the resulting feature space consisted of three thousand six hundred points (*i.e.*, six hundred points × six subjects). The test data set consisted of the data of the remaining subject. This process of leave-one-out cross-validation was repeated to assess the classification accuracy across all subjects. Classification accuracy was calculated as the percentage of correctly classified epochs for each part of the data (*i.e.*, first or last minutes of task). All of the processing steps are presented in Figure 7.1.

2.6. Statistical analysis

Statistica software (version 7.0, Statsoft, Oklahoma, United-States) was used for all analyses. All data were examined for normality using skewness and kurtosis tests. The Student t-test was used to test for any significant effect of time (*i.e.*, first ten versus last ten minutes of the task) on the changes in RT. Effect size was calculated on the RT values using Cohen's effect size d (d effects: small ≥ 0.2, medium ≥ 0.5, large ≥ 0.8), defined as the mean change score divided by the SD of change [57]. The significance level was set at $p < .05$. Data are presented as mean ± SD.

3. Results

3.1. Behavioral results

As expected, the RT results demonstrated that attention decrement occurred towards the end of the task. The Student t-test demonstrated that RT values were significantly higher in the last ten than for the first ten minutes of the task ($t_6 = 3.1$; $p < .05$). The Cohen's effect size d value for this difference was 0.7, corresponding to a medium-to-large effect. These results are presented in Figure 7.3. The RPE score after the experiment was 14.9 ± 1.7, a value corresponding to "hard" according to the scale.

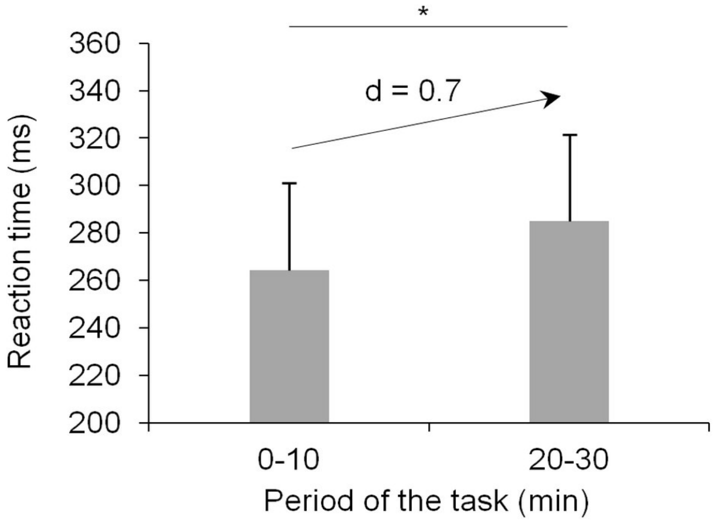

Figure 7.3: Changes in mean reaction time from the first ten to the last ten minutes of the task. A significant increase in RT occurred at the end (last ten minutes) compared to the beginning (first ten minutes) of the task. Cohen's effect size d value for this difference is specified above the centered arrow. * p < .05. Vertical bars represent SD**.**

3.2. Classification accuracy

All the classification accuracy results, including analyses exploiting [O_2Hb], [HHb] and both [O_2Hb] and [HHb] as features of interest from the PFC area exclusively, the right parietal area exclusively and both the PFC and the right parietal areas, are presented in Figure 7.4 and 7.5[94]. The main results indicate that *(i)* the highest classification accuracy results were obtained when exploiting the [O_2Hb] signals (*i.e.*, from 77 to 89 %, depending on the cortical area considered) rather than the [HHb] signals (*i.e.*, from 65 to 66 %) and *(ii)* the classification accuracy was increased to about 90 % when using signals from the right parietal area rather than from the PFC.

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[94] Please note that only Figure 7.5 is present in the published version of the article as it provides the main results of the classification analyses in terms of *classification accuracy*. Figure 7.4 has been however added in the present chapter because it provides relevant and more detailed information regarding the *specificity* and *sensitivity* results for each performed analyses.

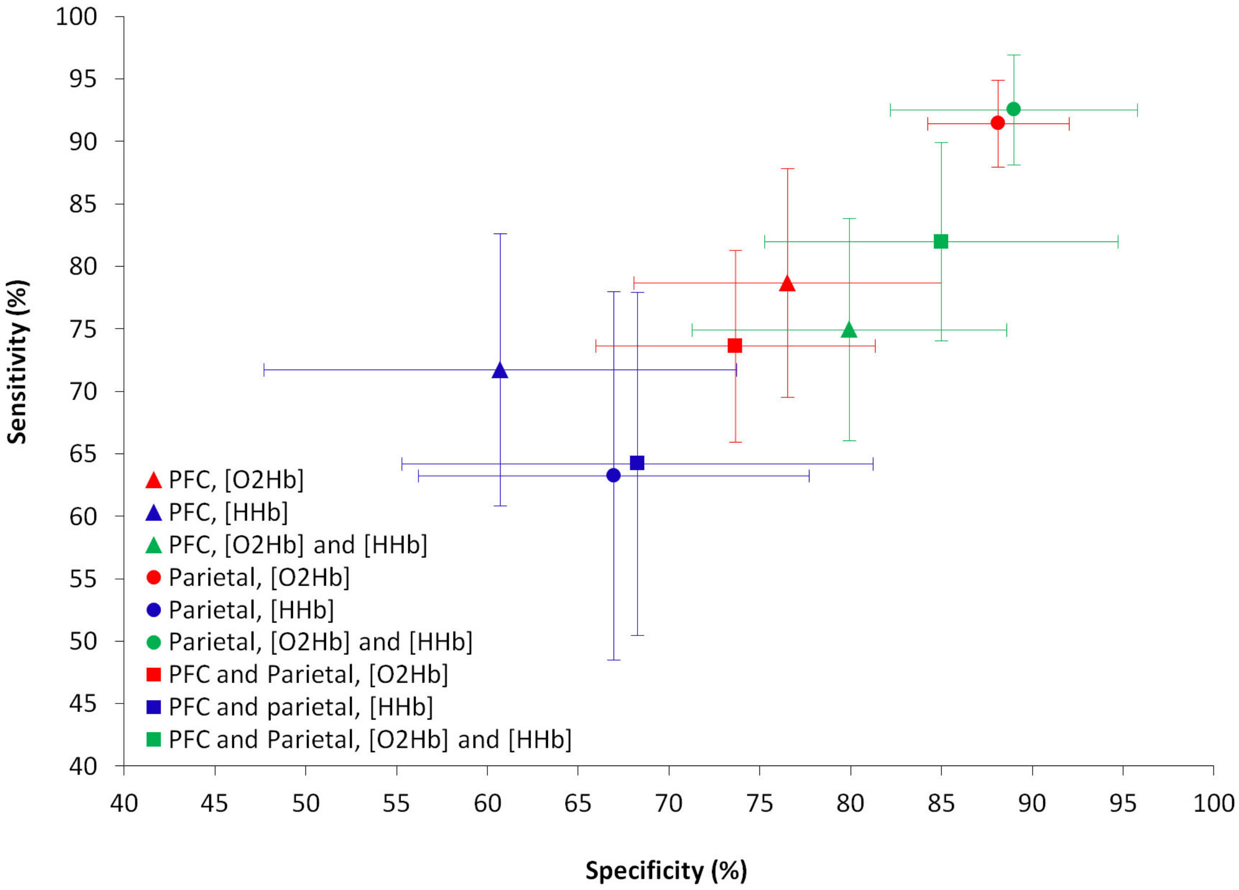
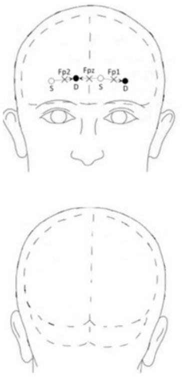


Figure 7.4: Sensitivity-specificity relationship as obtained for each analysis. Triangles represent the results of the analyses performed based on PFC signals. Circles represent the results of the analyses performed based on parietal signals. Squares represent the results of the analyses performed based on both PFC and parietal signals. Blue, red and green are exploited to represent the results of the analyses performed based on [HHb], [O_2Hb], and both [HHb] and [O_2Hb], respectively. Results are presented as mean ± SE.

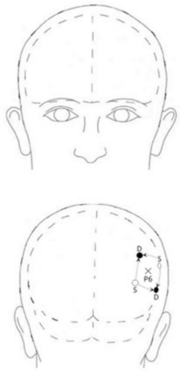
A.

Subject	[O2Hb]	[HHb]	[O2Hb] and [HHb]
1	44.5	87.8	88.8
2	73.5	94.2	89.1
3	49.2	28.4	32.1
4	95.1	90.4	90.6
5	98.4	80.6	76.5
6	82.5	21.2	68.3
7	100	60.8	96.7
Mean ± SD	**77.6 ± 23**	**66.2 ± 30.3**	**77.4 ± 22.2**



B.

Subject	[O2Hb]	[HHb]	[O2Hb] and [HHb]
1	94.9	94	99.6
2	85.4	81.6	97.9
3	91.7	22.6	77
4	100	26.4	91.3
5	83.8	45	72.2
6	76.3	86.1	100
7	96.4	100	97.2
Mean ± SD	**89.8 ± 8.3**	**65.1 ± 32.8**	**90.7 ± 11.5**



C.

Subject	[O2Hb]	[HHb]	[O2Hb] and [HHb]
1	60.8	100	91.8
2	85	96.5	96.3
3	39.8	6.6	34.2
4	92	34.5	96.7
5	94	61.4	74.7
6	75.5	70.7	93.9
7	92.2	93.9	96.8
Mean ± SD	**77 ± 20.2**	**66.2 ± 35.1**	**83.5 ± 23.1**

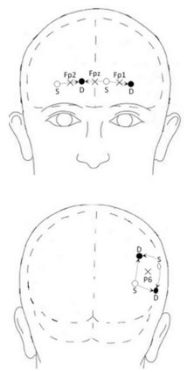


Figure 7.5: Detailed classification accuracy results using NIRS signals from the prefrontal (A), the right parietal (B) and both the prefrontal and the right parietal areas (C). From left to right, the columns present *(i)* subject number, the classification accuracy - in percentage of total classification trials - exploiting *(ii)* [O_2Hb], *(iii)* [HHb] and (iv) both [O_2Hb] and [HHb] as features of interest.

4. Discussion

This study aimed to investigate the potential of harnessing NIRS-measured cortical activity for the detection of time-on-task related changes in the level of attention during a sustained attention task. Our experimental design produced a decrement in the level of attention as revealed by the significant increase in RT in the last ten compared to the first ten minutes of the task ($p < .05$; $d = 0.7$). The results demonstrate that relatively good classification accuracy can be obtained using NIRS variables ([O_2Hb] and/or [HHb]) to detect the changes in the attentional state observed at the behavioral level. It is worth noting that the classification accuracy was lowest when exploiting the [HHb] signals only (*i.e.*, from 65 to 67 % in average), regardless of the cortical area considered. Moreover, the classification accuracy was increased to about 90 % when using signals from the right parietal area. These findings are examined in detail next.

4.1. Methodological considerations and study limitations

As already mentioned, the task studied here closely replicated the characteristics of the PVT developed by Dinges *et al.* (1997) and an increase in RT has been previously demonstrated for such a PVT, even for a task of twenty minutes duration (Lim et al., 2010). As expected, a significant increase in RT occurred during this simple RT task of thirty minutes duration. In addition to the longer RT, relatively high RPE values were reported by the subjects (*i.e.*, 14.9 ± 1.7 on a scale ranging from 6 to 20), which demonstrates the cognitive loading (sustaining of attention) demanded with such a simple sustained attention task (Langner and Eickhoff, 2012). Also, Lim et al. (2010) have shown that the increase in RT observed during their simple RT task of twenty minutes duration was accompanied by high subjective fatigue ratings after the task - subjective fatigue being well-known to affect sustained attention abilities (Boksem et al., 2005). Taken together, these results support the conclusion that the task exploited in the current study induced a time-on-task related attention decrement.

As discussed by Shen et al. (2008), one weakness of past studies exploiting EEG to detect attention decrement was the lack of subject-wise cross-validation in their performance evaluation (*e.g.*, Lal et al., 2003). We therefore applied, as in Shen et al., (2008), a "*leave-one-out*" scheme (which is a conventional approach to evaluate the performance of machine learning methods for small data sets) in order to evaluate the subject-independent accuracy performance. Using this leave-one-out cross-validation procedure, high classification accuracy was confirmed with up to 90% scores achieved in classifying attention state based on NIRS signals. The use of such a cross-validation procedure was particularly appropriate in this study as we had a relatively small number of subjects (n = 7), a small sample size which may be considered a study limitation. It is worth adding the caveat that leave-one-out schemes may induce, for small sample sizes, a bias in the error estimation (Beleites et al., 2005). Using a larger number of subjects would facilitate the exploitation of other validation schemes such as *k*-fold cross-validation which may afford less biased estimations of the model generalization error.

Another potential issue in the current study was the lack of control for any skin flow contributions to the NIRS signals and again, this may be regarded as a study limitation. Recent studies have raised the issue of superficial - extra-cortical - contributions in NIRS signals, specifically in the [O_2Hb] signal (Kirilina et al., 2012). The analysis of the photon time-of-flight distribution in time-domain NIRS (Aletti et al., 2012; Re et al., 2013) or the use of additional short emitter-detector separation as regressors (Gagnon et al., 2012; Sageer et al., 2011) have been proposed as methods to separate cortical and extracortical contributions in NIRS signals. In the study described here, the clear variability in attention decrement-sensitivity across the cortical areas investigated does not support the idea of a global systemic response biasing the feature space. The observed increased activity from areas known to be involved in attention suggests that the features identified reflect localized cortical vascular dynamics. The use of the aforementioned methods would have however helped identify the precise nature of the contribution from cortical components in the optical signals obtained.

The regional variation in the DPF identified in the literature (Hoshi, 2005) might also have affected the measured regional changes in NIRS signals. We exploited a subject-specific DPF based on the age of each subject as proposed by Duncan et al. (1996) and this allowed the measurement to be converted into changes in concentration levels of [O_2Hb] and [HHb]. In order to eliminate the heterogeneous effect of regional DPF variations across the full extent of the measurement area, the signals were normalized through expression in terms of percentage changes (Figure 7.1.B.). Future NIRS investigation might however implement region-specific DPF in addition to subject-specific DPF.

Finally, our classification procedure specifically aimed at classifying attention decrement-related lapses in attention, as they occur during time-on-task activities. To do so, we exploited the first and last ten minutes of the task to label our classes. An alternative means to detect changes in the level of attention could involve labeling the brain states of interest using moment-to-moment variations in behavioral performance (*e.g.*, RT). Doing so would facilitate the detection of changes in the level of attention on shorter time scales, as they occur momentarily, but such an approach is beyond the scope of the current study.

4.2. Region of interest: right parietal area versus PFC

This study aimed, in part, at testing the appropriateness of focusing on the PFC to detect decrements in the level of attention. The emphasis on the PFC which has characterized research to date in this field (Butti et al., 2006a, 2006b; DeJoux et al., 2013; Helton et al., 2007; Li et al., 2009; Shaw et al., 2013; Warm et al., 2008) has probably been as a consequence of an *a priori* knowledge-driven choice (*i.e.*, the PFC area has been identified as involved in a large number of cognitive functioning studies) and because of technical advantages that presents this hairless scalp area conveniently for NIRS investigation. In contrast, our experimental investigation has taken a data-driven approach to deduce which of the attention-related cortical areas offers the best classification accuracy when investigated using NIRS. We hypothesized that, given its implication in sustained attention tasks, the right parietal area would represent another potentially relevant candidate area over which to discriminate changes in the level of attention.

For both analyses, based on the PFC or on the right parietal area signals, relatively good classification results were obtained, however performance was on average much better when exploiting NIRS signals recorded over the right parietal area (see Figure 7.5.B). This finding is not surprising when one considers the aforementioned, crucial role of this area in sustained attention tasks (Coull, 1998; Fink et al., 1997; Pardo et al., 1991; Posner and Rafal, 1987). This result raises design dilemmas for NIRS-based cognitive-state tracking technology:

would it be preferable to focus on the right parietal area – which yields better discrimination and reduces then the possibility of false positives in the detection of attention decrement? Or rather, would it be better to continue to focus on the PFC which offers undeniable technical advantages for NIRS investigation, but offers poorer sensitivity to attention decrement? Although the presence of hair over the parietal area did not impact the classification accuracy results of our study, it was technically more complex, and hence took more time to set up than when measuring over the PFC. The problem of obtaining qualitatively good NIRS signals over hair-covered scalp areas is well-known from NIRS investigators and has been identified as an issue in motor area-based brain-computer interface design (Coyle et al., 2007). The challenge for future NIRS technological developments is to provide a NIRS optode mounting system which can resolve this problem of hair-related photon absorption. In such conditions, focusing on the right parietal area for detecting attention decrement in a real world context could become more convenient. It is worth commenting too that the positioning of probes over the parietal cortices is likely to be much more acceptable to users given that it is aesthetically less intrusive than the alternative which would require the mounting of a set of optodes and sensing technology on the face (*i.e.*, the forehead).

Finally, it is worth commenting on the finding that combining signals from both the PFC and the right parietal areas did not improve classification performance accuracy over the use of features from the right parietal area only in our classification analyses. This result potentially indicates that, rather than being additive or even multiplicative, information extracted from neural signatures of attention decrement over the PFC and right parietal areas may be redundant. In the purpose of developing practical, ambulatory cognitive-state tracking technologies, we previously mentioned that the number of measurement channels required at the scalp level should be minimized. Thus, the right parietal area may, on its own, represent an appropriate measurement area for NIRS-based detection of attention decrement.

4.3. Variable of interest: [O_2Hb] versus [HHb]

The second objective of this study was to determine which NIRS variable(s) should be exploited for the purpose of distinguishing changes in the level of attention. As mentioned in the introduction, some authors failed to find any changes in [HHb] in response to time-on-task, even during a sustained attention task of 3 hours duration (Li et al., 2009). The classification results here support the results of Li et al. (2009), and provide further evidence that the [HHb] variable has poor sensitivity to time-on-task related changes in the level of attention. This result can be explained by the existence of smaller changes in [HHb] compared to that in [O_2Hb] during neurovascular coupling - a phenomenon well "represented" by the balloon model (Buxton and Frank, 1997). Also, changes in [O_2Hb] have been described to more directly reflect cortical activation than [HHb] due to its superior contrast-to-noise ratio (Strangman et al., 2002), and previous NIRS studies have even proposed that researchers should focus on [O_2Hb] - rather than [HHb] - as the variable of interest to determine changes in cortical activity (*e.g.*, Derosiere et al., 2014b; Yamanaka et al., 2010).

The combination of both [O_2Hb] and [HHb] variables in our classification analysis, in some cases improves performance. This increase is minor when measured over the right parietal area (about 1 %) and the combination of variables in that example is of minimal utility. As one problem in developing useful cognitive-state tracking technologies is that of reducing its computational requirements (Johnson et al., 2011) here again, a choice has to be made between two alternatives, that is: either *(i)* exploiting both the [O_2Hb] and the [HHb] variables as features of interest in order to marginally improve performance at the cost of increased computational overhead (*i.e.*, by doubling the dimension of the feature space) or *(ii)* focusing on the [O_2Hb] to reduce the computational cost with a minor loss in classification performance. In our opinion, the latter alternative appears to be the more appropriate choice for the purpose of future real-time applications although it depends on the precise use-case envisaged.

5. Conclusion and perspectives

To the best of our knowledge, this study is the first to describe an approach to detect changes in the level of attention through monitoring hemodynamic signals and the results may serve as a further step towards the development of a NIRS-based cognitive state tracking system. Our data-driven approach leads to the conclusion that *(i)* the right parietal area represents a better choice for the positioning of optodes as it is less intrusive and more sensitive than the PFC and *(ii)* the [O_2Hb] variable appears to be sufficiently sensitive for characterization of attention decrements as they occur in cortical areas. The results also demonstrate that optical neuroimaging constitutes a relevant method of significant potential for cognitive state monitoring. We feel the method may have most benefit through integration within a hybrid system context where a combination of complementary modalities (*e.g.*, EEG and NIRS) may provide more robust performance over each modality used in isolation.

Acknowledgments

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6. Supplementary materials

Following helpful discussions with the PLOS One reviewers, I felt necessary to add further information on two main technical points, not discussed in details in the paper as published in its current form.

The first point regards to the choice we made for a SVM classifier instead of a LDA, also widely exploited in data mining (Izenman, 2008). Similarly to the SVM algorithm we used in the current study, LDA uses an hyperplane to separate the several classes to be tested (please see Chapter V). The main difference between LDA and SVM algorithms resides in the absence of a margin surrounding the hyperplane in the former as compared to the latter. In order to check for any effect of the type of classifier on our classification accuracy results, we performed all our classification analyses with LDA and compared to the results obtained using a SVM algorithm. The results are presented in Table 7.1, hereafter.

Classification accuracy results using a LDA classifier for each combination of features of interest

	[O_2Hb]	[HHb]	[O_2Hb] and [HHb]
Prefrontal	85.8 ± 17.4	70.3 ± 28.2	80.3 ± 23.4
Parietal	90.4 ± 11.2	65.0 ± 33.8	89.3 ± 15.0
Prefrontal and Parietal	88.9 ± 7.2	71.2 ± 35.5	81.1. ± 23.3

Table 7.1: Results are presented as % of correct classification over total classification trials (presented as mean ± SD).

One may observe that, overall, the use of LDA produces similar results and leads to the same conclusions regarding the superiority of the parietal location and [O_2Hb] signals as when using a SVM algorithm. This result is of strong importance as it evidences the robustness of our classification accuracy results. It does however not bring further information on our choice for SVM instead of LDA. Our choice of using SVM was based on the basic technical advantages of this type of classifiers over LDA. Indeed, as Shen et al. (2008) stated: "*Unlike other statistical learning methods (such as neural networks and decision trees) which usually aim only to minimize the empirical classification error, SVM simultaneously minimizes the empirical classification error and maximizes the geometric margin in classification; hence, it is also known as maximum margin classifier (Boser et al., 1992; Cortes and Vapnik, 1995; Vapnik,1998; Cristianini, 2000)*". This maximization of the margin confers to the SVM its specificity and is at the origin of its widespread use in data mining and especially in active (*e.g.*, Sitaram et al., 2007) and passive (*e.g.*, Shen et al., 2008) BCIs. I decided not to detail the results obtained using LDA in the PLOS One paper, as a comparison of classifiers for attention-related NIRS signals falls outside the stated scope of the study.

The second concern of one of the reviewers was with regards to **what** we actually classified while exploiting the ten first and the ten last minutes of the task to label our "*full attention*" and "*attention decrement*" classes, respectively. The reviewer questioned in particular if there was any possibility that our classification results could actually reflect non-stationary components (instrumental) present in the NIRS signals, in which case would manifest as signal drift over time. However, a number of arguments led to the conclusion that this was not the case. First, in terms of instrumentation drift, light emitting diodes (LEDs) can indeed provoke drifts in the recorded signals, as they may warm up over time resulting in increased optical efficiency and subsequently optical output inducing drift in the measured signals (*e.g.*, in Kirkpatrick et al., 1995; Muehlemann et al., 2008). However, the Oxymon Mk III system that we exploited in our study is laser-based, not LED-based, and the potential for the aforementioned instrumentation drift can be rejected. In any case, Muehlemann et al. (2008) conducted signal phantom drift measurements with LEDs and found that drifts ranged from 0.024 to 0.087 % of the NIRS signals' amplitude while for a given functional task cortical changes in NIRS signals' amplitude were of the order of 4 to 8 %. The authors concluded: "*compared to the signal intensity changes of approximately 4 % for the 760 nm light sources and 8 % for the 870 nm light sources in the described brain activity experiment, the drift can be neglected*". Following this line of inquiry, Kirkpatrick et al. (1995) chose to selectively analyze periods of 30 to 60 minutes of NIRS signals from recordings of several hours, as they observed that drifts for such periods were very small, even using LEDs. Second, let's suppose that a drift occurred in our NIRS measurements and can be taken as an alternative explanation for our classification accuracy results. This would involve that the hypothetical drift was consistently the same for a given channel in every subject since we have been able to correctly classify what would be then drift-related NIRS signal changes, even using a LOOCV scheme including all subjects. As an illustration, it would imply for instance that *(i)* channel 1 presented a positive drift with a large slope, and this for every subjects; while *(ii)* channel 2 presented a negative drift with a small slope, and this for every subjects; while *(iii)* channel 3 presented a positive drift with a small slope, and this for every subjects; *etc.*, and all this, in a very reproducible manner. Even stronger, one would conclude that these hypothetical drifts in NIRS signals would be more reproducible between subjects when measured over the parietal cortex than when measured over the PFC, as better classification accuracy was obtained using signals from the parietal areas using a LOOCV scheme. The similarity in the changes in NIRS signals between each subject, and the dissimilarity in the changes in NIRS signals between scalp regions, are more likely to represent robust changes in attention-related cortical activity associated with changes in the level of attention. Finally, to definitely ensure the quality and integrity of our signals, we provide the reader with typical NIRS signals as recorded over 1 subject (Figure 7.6). One may notice that there is no overall long-term trend in the channels, as it would have been potentially the case if drifts had affected our measurements. Rather, [O_2Hb] signals increased only from the middle of the task over the right parietal area. Also, [O_2Hb] values went down over certain regions as in the mPFC, while LPFC showed increased [O_2Hb] signals throughout the task.

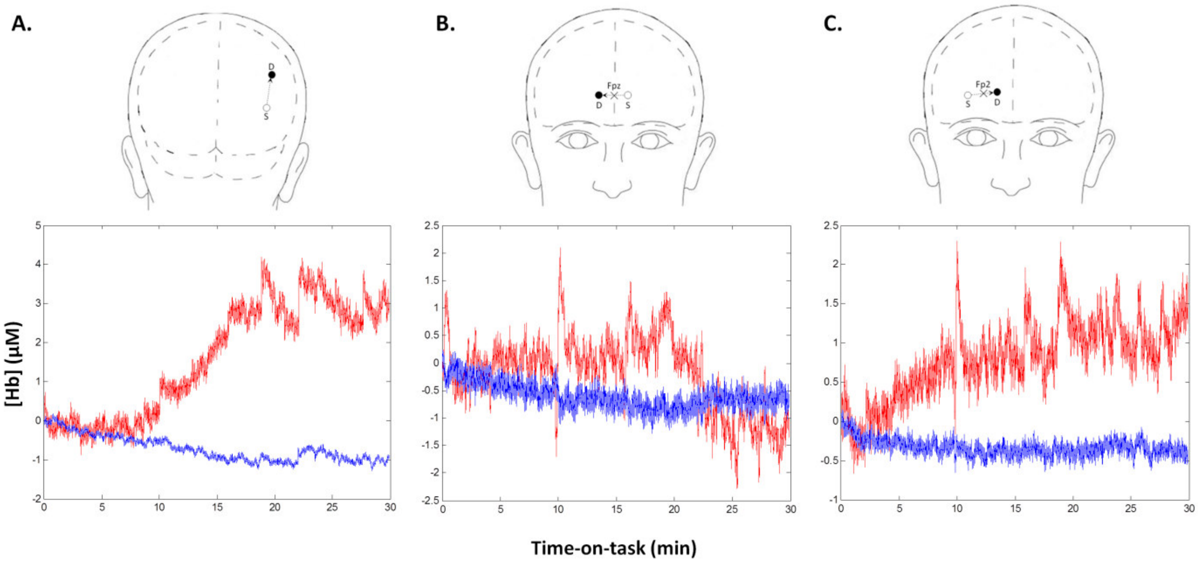

Figure 7.6: Typical NIRS signals dynamics as measured throughout time-on-task during a sustained attention task over A. the right parietal area, B. the mPFC, and C. the right LPFC. Red and blue traces represent [O2Hb] and [HHb], respectively. Note that these are raw signals, neither low-pass filtered, nor artifact-free.

The antagonistic patterns over the attention-related cortical areas observed in Figure 7.6 are well-known in the attention literature (please see Chapter III, p. 162, for related discussion) and have not only been observed for this single subject, but are also present in averaged changes in signal amplitude as presented in Figure 3.4, p. 157. As described by Fox et al. (2005), when increasing the cognitive load in attention-demanding tasks, certain attention-related areas routinely exhibit decreased activity (*e.g.*, mPFC; Gusnard and Raichle 2001), and others, such as LPFC and right parietal areas, demonstrate activity increases (Cabeza and Nyberg 2000). Last but not least, the results presented in Derosiere et al.

(2013b)[95] regarding the proportional increase in classification accuracy as a function of the increase in RT also demonstrate that NIRS-based classification accuracy results were tightly related to impairment of behavioral performance with TOT. Taken together, the points developed here strengthen the argument that our classification accuracy results did stem from cortical activity changes related to alterations in the level of attention, rather than simple signal drifts. These supplementary materials substantially reinforce our conclusion regarding the potential of harnessing NIRS-measured cortical activity for the detection of TOT-related changes in the level of attention during a sustained attention task.

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[95] **Published as**:
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- PART III -

EPILOGUE

Chapter VIII

General Discussion

Towards a disentangling of the neural correlates of attention decrement

"*To understand is to perceive patterns*."

Isaiah Berlin (1997)

1. Synthesis of contributions

1.1. What did we know tens of pages ago...

That attention is a vital cognitive function; that attention is involved in a countless number of human beings' sensory-motor activities, extending from the neurosurgeon operations to the violin beginner practice; that, nonetheless, attention cannot be maintained at an optimal level indefinitely; and that attention decrement is manifested by sensory-motor deficiencies, which can crucially impact human beings' daily activities (*e.g.*, Robertson, 2003): this was, in part, what we knew tens of pages ago. Yet, this thesis started with a paradoxical observation: the neural correlates of attention decrement had been so far under-investigated (Langner and Eickhoff, 2012). The need for further knowledge about the neural correlates of attention decrement was then clearly perceived within two different disciplinary fields: Cognitive Neuroscience and Cognitive Engineering.

On the one hand, in Cognitive Neuroscience, the theoretical accounts that had been until then provided to explain why human beings are unable to maintain states of focused attention were incontestably lacking support from brain data[96]. While the resources theory of attention decrement had been undermined by the few available neuroimaging findings of the literature, the explicative power of the mindlessness theory could have been further improved if a more detailed knowledge of the neural underpinnings of the phenomenon was available. One specific weakness of the field, identified at the end of **Chapter I**, was that the sensory-motor neural correlates of attention decrement was absolutely unknown while, strikingly, the phenomenon is basically characterized by sensory-motor deficiencies. However, the literature review developed in **Chapter I** did provide scattered clues which indicated that attention decrement could be hypothetically associated with: *(i)* an active inhibition of the sensory cortices; *(ii)* an over-excitability of the motor neural structures; and *(iii)* an over-engagement of attention-related cortical areas.

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[96] This even seems paradoxical: how can a Cognitive Neuroscience approach lack brain data? As introduced in Chapter I, some neuroimaging studies did investigate the neural correlates of attention decrement but most of the efforts in Cognitive Neuroscience of Attention had been so far made in better understanding the neural correlates of attention functions in full capacities conditions. The research area on attention decrement offered then huge avenues for further research.

On the other hand, in Cognitive Engineering, there was a need for investigating the reliability of brain signatures of attention decrement as novel inputs to cognitive-state tracking systems (*i.e.*, as identified in **Chapter V**). In fact, this field of investigation had been so far mainly focused on the detection of sleepy states and cognitive-state tracking systems were then essentially based on physical and psycho-physiological markers of the level of wakefulness. Although these systems had proven an ability to offer relatively high levels of classification performance, they did not allow for detecting changes in the level of attention that were unrelated to sleepy states. The recent emergence of passive BCI as a particular type of cognitive-state tracking system however suggested that cortical activity could provide a relevant input to detect more subtle changes in the attentional state during sustained attention tasks.

1.2. ...and what about now?

In accordance with these observations and based on the two above-mentioned disciplinary fields, the present thesis developed a thorough investigation of the neural correlates of attention decrement.

On a Cognitive Neuroscience point of view, this thesis sought to shed further light on the neural underpinnings of the sensory-motor deficiencies associated with attention decrement. The major contributions of the present work in this domain result from a relatively novel and original approach which has consisted in focusing on the roles of the sensory and motor neural structures in the development of the phenomenon. Through such an approach, we were able to reveal that attention decrement is associated with an inhibition of the sensory cortices, which is likely to represent the neural underpinning of the decrease in perceptual sensitivity and the increase in RT characterizing the phenomenon [97] (**Chapter II**). Furthermore, we demonstrated an increase in the excitability of the motor neural structures with TOT which may offer an explanation to the increase in motor impulsivity often observed with attention decrement (**Chapter III**). Finally, as a secondary contribution, this thesis confirmed previous results of the literature (*e.g.*, Coull et al., 1998) regarding the over-

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[97] This interpretation is strongly supported by previous studies of the literature that demonstrated that the level of prestimulus alpha power in occipital cortices is negatively correlated with the subjective perception in visual detection and discrimination tasks (Hanslmayr et al., 2007; Wyart and Tallon-Baudry, 2009; Romei et al., 2010).

engagement of attention-related cortical areas over TOT (*i.e.*, LPFC and right parietal area; **Chapter III**).

From a Cognitive Engineering point of view, this thesis examined the reliability of using NIRS-measured attention-related areas' activity as a marker of attention decrement and potential input to passive BCI. The major contributions of the present work in this domain result from a combination of knowledge- and data-driven approaches. Firstly, the Part I of this thesis[98] allowed us to establish that the prefrontal and right parietal cortices would represent areas of interest to detect attention decrement through a passive BCI given that *(i)* these cortical areas are involved in a large number of attention-related sensory-motor activities; and that *(ii)* their activity was evidenced to significantly change with attention decrement, both in the literature (*e.g.*, Coull et al., 1998) and in Chapter III. Secondly, based on this prior knowledge, a data-driven approach has allowed us to examine which attention-related area and which NIRS-measured hemodynamic variable would offer the best input to passive BCIs in terms of classification performance. Following this line of reasoning, the present thesis provides novel and exciting findings, demonstrating that signals from the right parietal area provide better classification accuracies than signals from the PFC (**Chapter VII**). These results challenge the past commonly used approach of NIRS investigation in Cognitive Engineering[99] which, as identified in **Chapter VI**, focused exclusively on PFC activity. Further, our data-driven approach led to the conclusion that the [O_2Hb] variable would offer better classification performance than the [HHb] variable for detecting attention decrement. All in all, these different findings provide a basis for the future establishment of "*guidelines*" for cognitive engineers interested in developing NIRS-based passive BCIs.

The contributions of this thesis are anything but constrained to the above-described results. To go a step further in our investigation, I indeed develop a deeper discussion of these different results in the next sections. These *general discussions* can be considered as the last - but not least - contributions of the present work.

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[98] That is, Part I - Cognitive Neuroscience.

[99] More specifically in Neuroergonomics.

2. Attention decrement under the scope of Cognitive Neuroscience

As I stated at the very beginning of the present manuscript, "*What*, *how* and *why* represent the three identified hierarchical levels of investigation in Science" (Prediger et al., 2008). Based on a detailed literature review (*i.e.*, Chapter I), I first determined *what* neural structures are involved in the sensory-motor deficiencies associated with attention decrement. Then, the experimental contributions described in Chapters II and III enabled us to bring to light *how* these neural structures behave over time during sustained attention tasks. Finally, the issue of *why* those neural structures behave the way they do has been addressed in an initial step of discussions, partly in Chapters II and III, and in Chapter IV. The present section is in continuity with these discussions. Before addressing the issue of attention decrement, I first provide a personal reflection about the very essence of focused attention on the basis of the neural findings reported in this thesis.

*2.1. Reflection about the very essence of focused attention: a winner-take-**almost**-all process?*

Our findings do not only offer a better understanding of attention decrement but also eventually contribute to reveal the very essence of focused attention. As I briefly discussed in Chapter IV (please see p. 168), the finding of an increase in LPFC and right parietal areas' activity with TOT (Chapter III)[100] demonstrates that these structures were not maximally engaged at the beginning of the attention task. This observation is of substantial importance for our understanding of humans' cognition: it implies that when individuals engage in a given focused attention task, the "processing resources" (*i.e.*, the neurons of attention-related brain structures) are not fully recruited and a "*cognitive reserve*" remains available. Also, given the top-down-related function of the LPFC and right parietal areas, a restriction in their activity may have a potential influence on the activity of the motor and sensory neural structures. The results presented in Chapter III indeed suggest that the motor neural structures[101] were engaged at the beginning of the RT task but not maximally. Yet, only one motor plan was

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[100] This is worth remembering that our study is not isolated in its findings. Similar results have been indeed reported in the literature (*e.g.*, Butti et al., 2006a, 2006b; Coull et al., 1998).

[101] That is, M1 area and CS tract.

selected and made possible (*i.e.*, right thumb abduction) in the task the subjects were required to realize in this study and there was *a priori* no need to restrain the neural facilitation in favor of this action. It seems thus that such a restriction in neural facilitation is an inherent characteristic of focused motor attention, occurring even when the level of competition between potential motor plans is minimal[102]. Following the same line of reasoning, it is sensible to assume that, during focused sensory attention, the facilitation of the sensory neurons coding for the attended stimulus may not be maximal. Some findings of the literature indeed evoke the existence of such a restriction in neural facilitation in sensory cortices. For example, Herrero et al. (2008) demonstrated that it was possible to increase the firing rates of visual neurons during focused visual attention through Ach injection, although the activity of these neurons was already enhanced by focused attention. In summary, while certain models of decision-making and spatial attention have depicted information selection as a winner-take-all process (*e.g.*, Koch and Ullman, 1985), the results reported in this thesis and other results of the literature (*e.g.*, Herrero et al., 2008) rather suggest that both motor and sensory attention work as a "winner-take-*almost*-all" process: focused attention indeed facilitates selected perceptions and actions, but not too much. This modulation in the definition of how focused attention acts on the selected actions and perceptions strongly reminds us of the contentions that occurred in the early years of cognitive psychology regarding how attention acts on ignored sensory stimuli. On the one hand, Broadbent (1958) defended the theory that attention acts by completely filtering out the representation of ignored stimuli at an early stage in the "*information processing system*"[103]. On the other hand, Treisman (1960) claimed that attention rather acts by attenuating the representation of ignored stimuli in the "*information processing system*" (please see Chapter I, pp. 38-40). Later on, Treisman's theory was supported by Cognitive Neuroscience studies which described that focused attention does not completely shut down the activity of neurons coding for ignored stimuli and unwanted actions but rather reduce the level of excitability of these neurons through inhibitory processes (*e.g.*, Anton-Erxleben et al., 2009; Anton-Erxleben and Carrasco, 2013). All these elements lead to the conclusion that focused attention works, somehow, by applying weights to the neural representation of attended and unattended perceptions and actions, with a certain balance.

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[102] In this case, the level of "competition" between potential motor plans can be even considered as null. In the case of a choice RT task, several motor plans would have been to be prepared and mutual inhibitory interactions could have influenced the neural facilitation related to focused motor attention.

[103] According to the terminology exploited at this period.

Why are things the way they are? *Why* does focused attention work based on such a weighted balance of inhibitory and facilitatory processes? *Why* are the neural facilitations of attended perceptions and actions restrained instead of maximal? If focused attention functions in this way, then there must be a functional interest. It is sensible to assume that the restriction in facilitation of attended perceptions and actions is at the very basis of humans' behavioral flexibility. Accordingly, states of "over-facilitation" are known to negatively impact human beings' cognition and behaviors. For example, one such state of over-facilitation occurs as a side effect of the psycho-stimulant drugs prescribed to ADHD patients (*e.g.*, Ritalin). These patients experience *over-focused* attentional states which are characterized by an inability to switch their attentional focus from one task to another (*e.g.*, Solanto and Wender, 1989). And this kind of attentional state does not limit itself to pathological cases. The phenomenon of attentional tunneling which can be observed in healthy subjects (Wickens and Alexander, 2009) indeed belongs to the same type of attentional dysfunctions. In attentional tunneling, attention is basically *over-focused* on a given sensory or cognitive stimulus and can be thus less flexibly switched from this stimulus to another. In a quite similar vein, patients with obsessive-compulsive disorders (OCD) are affected by an over-focusing on their pathological thoughts which negatively impacts their capacities to focus attention on sensory stimulus (Clayton et al., 1999). In these different cases, too strong a "weight" is applied to the facilitation of the sensory or cognitive (*e.g.*, thoughts) stimuli on which attention is focused and this subsequently alters the normal functioning of perception and cognition.

Following the same line of reasoning, at the motor level, the restriction in neural facilitation may allow us to flexibly switch from one motor plan to another (for a related discussion, please see Chapter IV, p. 168). But in the case of motor attention, this may not be the only functional interest of this process. In fact, it may be assumed that the restriction in neural facilitation in focused motor attention also plays a substantial role in the timing of movement execution, as it prevents triggering selected movements at inappropriate moments. Consistent with these interpretations, during attention-related tasks, motor impulsivity symptoms and motor control deficiencies in ADHD patients have been related to an over-excitability of the motor cortices (*e.g.*, Heinrich et al., 2014). In this case again, too large a "weight" is applied to the facilitation of the action(s) on which attention is focused and this subsequently alters motor performance.

Focused attention appears to function then as a winner-take-*almost*-all process, a fact supported by the analysis of a number of attentional dysfunctions. In accordance with this definition of focused attention, the present work describes that attention decrement is associated with a motor over-excitability which may provide a neural underpinning to the increase in motor impulsivity often associated with the phenomenon. To go a further step in our analysis, the next two sections address the question of *why* such an over-engagement of motor (and attention-related) neural structures occurs over time during sustained attention tasks.

2.2. Disengagement of sensory cortices and related (neural) consequences

In biological organisms, *efficiency* is the watchword. This, for example, can be seen in the optimal control theory of motor coordination (Todorov and Jordan, 2002), describing that human beings inherently produce movements in an optimal way despite of (or based on) the multitude of degrees of freedom offered by their anatomies. Or in the theory of "*Simplexity*" (Berthoz, 2009) which depicts the humans' ability to perceive (and design) simple solutions in response to complex problems. Or else in the IOR process which prevents human beings from processing the same information several times. The ubiquitous presence of efficiency in biological organisms appears to be the basic consequence of natural selection (Darwin, 1859): efficient processes have been conserved over evolution as they have enabled to maximize survival. In this vein, it has been proposed that the IOR process has played a substantial role in foraging abilities during evolution (Klein, 2000): reexamining the same location several times while looking for food would have obviously been inefficient.

The present thesis upholds that attention decrement is causally related to the same kind of inhibitory process. During sustained attention tasks, the same location, the same object, the same stimulus with the same features, are processed over and over again. As proposed in the Part I of this manuscript, these repetitive aspects of perceptual stimulation are potentially at the basis of the increased inhibitory activity observed in sensory cortices over TOT (Chapter II). In fact, repetitively processing the same stimulus without interruption would lead to an increased cost for the same outcomes, and would be thus inefficient by definition. Following this line of reasoning, attention decrement can be considered as a by-product of evolution. The interesting question arises then of how this phenomenon, which negatively impacts humans' behaviors, may have indeed been conserved over evolution. Two points can be discussed with regards to this issue. Firstly, as Robertson and O'Connell (2010) defended "*One reason why the vigilant attention system may have evolved imperfectly is because there are survival advantages associated with periodic disengagement from the current focus of attention - in other words 'lapses'*". This indeed represents a compelling explanation: excessive periods of focused attention may have been dangerous for our ancestors as they could have "*become the preys themselves*", according to the terms exploited by Robertson and O'Connell (2010). This interpretation can be easily connected with our above-given definition of focused attention: such as over-focused states impact negatively on behavioral flexibility, keeping a high level of focused attention indefinitely during sustained attention tasks would lead to a certain behavioral rigidity. Secondly, evolution must not be taken as a process by which every single aspect of a biological organism is optimized but must rather be considered as an equilibrium between the conservation of efficient processes and related potential negative consequences. Nature overflows with illustrations of this assumption. Noor and Milo (2012) for instance remarked that while cheetahs are worse tree-climbers than leopards, they are the fastest land animals on Earth: their semi-retractable claws, a by-product of evolution, are an advantage in running but represent a clear disadvantage in climbing. In an evolutionary neuroscience perspective, human beings are a relevant example of this fact: while their more developed neo-cortex is the basis of higher cognitive abilities as compared to other species, it is also associated with a reduced olfactory bulb and relatively worse olfactory abilities (*e.g.*, as compared to turtles; Striedter, 2005). In this line, while the inhibitory process observed during sustained attention in sensory cortices may have once represented a survival advantage - and for that matter may still be strongly beneficial in visual search tasks[104], it is not free from disadvantages in human beings' contemporary activities. Scientists are nowadays more and more concerned with these disadvantages because of the increasing technological advances and related ubiquitous requirement of sustained attention in our daily living activities[105].

The sensory cortices' disengagement (*i.e.*, related to the increased inhibitory activity) occurring early in sustained attention is not without consequences on the activity of other neural structures. In fact, one of the points that the present thesis defends is that the early

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[104] This is of substantial importance: the inhibitory process observed during sustained attention within the sensory cortices may be for example strongly beneficial when one tries to visually find someone in a crowded place, as in the game "Where's Wally?". Thus, what is a beneficial in visual search tasks, is not in sustained attention tasks.

[105] Actually, it is only after World War II that the question attention decrement (and of attention) received considerable attention from scientists and this was related to the huge technological advances that accompanied the war and of their transfer to civilian applications.

sensory disengagement is at the origin of the increased activity of motor- and attention-related neural structures. This assumption was at the basis of the working hypotheses formulated in Chapter I and followed from previous work cited from the literature (*e.g.*, Weissman et al., 2006). Based on a trial-by-trial fMRI analysis, Weissman et al. (2006) demonstrated that *(i)* brief lapses in attention[106] were associated with a diminished neural response of the sensory cortices and that *(ii)* the trials following such brief lapses were consistently associated with an increased activity of attention- and motor-related cortical structures. The authors hence concluded that "*these systems*[107] *need to work harder to complete their processing when they receive relatively low-quality perceptual representations*". Similar results and interpretations have been provided in the literature in the context of sleep deprivation (Drummond et al., 2005). Even if the present thesis did not directly investigate the causal relationship between *(i)* the sensory cortices disengagement and *(ii)* the increase in motor- and attention-related neural structures' activity, several clues in the literature lead us to consider this interpretation as valid. This issue is addressed next.

2.3. Over-engagement of motor- and attention-related neural structures

Like efficiency, *compensatory processes* [108] seem ubiquitous in nature. Clinical neuroscience offers wonderful illustrations of this assumption. Stroke patients naturally tend to compensate their inability to use their affected arm, by developing novel motor skills with their unaffected arms[109] (Nakayama et al., 1994). Older adults compensate for the loss in efficiency of the left LPFC by recruiting the right LPFC during working memory tasks (*i.e.*, according to the "compensation hypothesis"; Park and Bischof, 2013; Cabeza et al., 2002). Parkinson patients experience a pre-symptomatic stage which is said to be "compensated" (Bezard et al., 2003): until the depletion of the striatal DA neurons reaches 80 % of the total number of neurons, almost no symptoms occur in these patients as several brain structures

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[106] A brief lapse in attention was defined as a momentary increase in RT followed by a recovery from this increase in this study. These brief increases were unrelated to TOT.

[107] That is, motor and attention-related cortical structures.

[108] By *compensation*, I refer to the way biological organisms adapt to a deficiency in a given structure and /or function by exploiting other structure(s) and/or function(s).

[109] This even led to the development of constraint-induced movement therapy (*e.g.*, Wolf et al., 2006) which specifically aims at avoiding the natural tendency of stroke patients for compensating their motor deficiency with the unaffected arm.

compensate this loss[110]. In these different examples, compensatory processes are easily perceptible given their long-term aspect. It is however likely that, on a shorter time scale as during a given cognitive or sensory-motor task, the human brain adapts itself in a moment-to-moment manner to its own internal state.

The present thesis asserts that, as an attempt to compensate for the disengagement of the sensory cortices, the motor- and attention-related neural structures over-engaged with TOT during sustained attention tasks. This assertion is not exclusively based on the observation that compensation is an intrinsic property of humans' brain physiology; it is complementarily supported by recently proposed decision-making models (Brown and Heathcote, 2005; Gold and Shadlen, 2007; Kiani and Shadlen, 2009; Pearson et al., 2009; Shadlen and Kiani, 2013; Smith and Ratcliff, 2004; Tandonnet et al., 2012). These models describe decision-making as a bounded-accumulation system binding perception, cognition and action together, in an integrative manner. In brief, in such bounded-accumulation systems, a decision will be made (*e.g.*, initiating a given movement in response to a given sensory stimulus) according to the levels of perceptual and motor evidence[111]. An initial alteration of the level of perceptual evidence (*e.g.*, a change in stimulus salience) would be likely to engender, in one way or another, an adaptation of motor neural structures' activity even if the level of motor evidence remains unchanged. A clear example of this kind of adaptation can be seen in the results of the recent study by Klein et al. (2014). These authors investigated the changes in CS excitability during the RT period (*i.e.*, in between stimulus occurrence and motor response) under conditions where the target stimuli were ambiguous (low perceptual evidence) or obvious (high perceptual evidence). They reported a higher CS excitability under the ambiguous condition, witnessing the negative relationship between the level of perceptual evidence and motor neural structures' activity. In the context of detection or discrimination tasks, the levels of perceptual and motor evidence are usually fixed: the target stimulus is unambiguous and does not change during the task, and only one motor response is made possible. However, during sustained attention tasks, the increased level of alpha activity observed over sensory cortices with TOT is likely to be associated with a decrease in the quality of perceptual representations, and thus the level of perceptual evidence (Hanslmayr et

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[110] The loss in nigrostriatal DA neurons is compensated by a decrease in striatal Ach activity, and in GABAergic neurons' activity in the striatum and SN (Lloyd, 1977).

[111] Perceptual evidence: evidence leading to the decision that a given stimulus is an imperative, target stimulus. Motor evidence: evidence leading to the decision that a given action is the appropriate action according to the contextual rules. Please see Gold and Shadlen (2007) for a more detailed explanation of the neural basis of these models in the context of simple RT.

al., 2007; Wyart and Tallon- Baudry, 2009; Romei et al., 2010). This is in this line that the present thesis puts forward that the motor- and attention-related neural structures' over-engagement is causally related to the sensory cortices disengagement during sustained attention tasks.

Another, and complementary, explanation that has been advanced in this manuscript is that the increased attention-related cortices' activity observed with TOT indicated an increasing need for re-directing the focus of attention to the sensory content of the task. In my opinion, attention decrement must not be considered as a all-or-nothing phenomenon in which one would switch from completely focusing on the sensory content of the task to fully focusing on endogenous, internal stimulus (*i.e.*, TUT). Instead, it must be considered that *(i)* sustained attention is inherently characterized by a series of focused states, alternatively directed to the exogenous (sensory) and endogenous (thoughts) stimuli (Smallwood, 2013); and that *(ii)* attention decrement represents the human beings' tendency to increasingly turn themselves to self-centered matters as time elapses (Braboszcz and Delorme, 2011). As such, the TOT-related sensory disengagement depicted in Chapter II provides a forceful explanation of this inherent tendency of human beings. The attention-related neural structures' over-engagement, meanwhile, is consistent with the interpretation of an increased need to re-direct the focus of attention to the sensory content of the task as time elapses.

An issue which is worthy of further consideration at this point of the manuscript concerns the conceptual definition that one may give to attention decrement based on the present work. In line with the literature review developed in Chapter I (pp. 107-109), this thesis maintains that attention decrement must not be considered as a decrease in the overall "level of attention", as resources theorists would argue. Instead, the present work depicts attention decrement as resulting from a decoupling between the exogenous stimulation provided by a given sustained attention task and the endogenous focusing of attention. That sensory cortices are actively inhibited with TOT (Chapter II); that, as a result, attention is increasingly focused on self-centered matters over TOT (Braboszcz and Delorme, 2011); that, as a potential consequence, motor- and attention-related neural structures need to work harder to keep coping with the task demand (Chapter III); and that, accordingly, perceptually unchallenging sustained attention tasks are subjectively perceived as strongly difficult (Langner and Eickhoff, 2012): all these elements support one another and compellingly reinforce the mindlessness theory of attention decrement.

2.4. Future avenues for research in Cognitive Neuroscience

"*A good idea is a network.*" Steven Johnson (2010)

In Science, the development of theoretical accounts must lead to testable hypotheses. In this line, the present work leads to a number of novel questions pertaining to Cognitive Neuroscience, out of which testable hypotheses clearly emerge.

The very first question that comes to mind with regards to the whole argument developed in this thesis is: *Does the level of perceptual demand in a given attentional task directly impact attention decrement?* My hypothesis, which can seem quite intuitive after these 240 pages, is that providing changes in perceptual stimulation in a sustained attention task would reduce the negative impacts of TOT on sensory-motor performance. Actually, this hypothesis - and for that matter, the whole theory defended in this thesis - (are) is strongly supported by practical observations: humans are for instance able to sustain attention in a relatively stable way over time when playing video games. To experimentally test this hypothesis, the temporal and spatial characteristics of perceptual stimulation, as well as the stimulus features (*e.g.*, pitch in the case of audition; or size, shape and color in the case of vision), should be manipulated in different versions of sustained attention tasks and the behavioral and neural outcomes could be then investigated. In my opinion, this kind of investigation must represent a priority for future research in the field as it will help create a more integrative view of humans' attentional functions, binding top-down (goal-directed) and bottom-up (stimulus-driven) attention processes together[112].

Another question that arises from the present work regards the causality between *(i)* the sensory cortices' disengagement and *(ii)* the motor- and attention-related neural structures' over-engagement. The discussion developed in the previous subsection undeniably leads to the hypothesis of the existence of such a causality. However, this hypothesis remains to be experimentally tested. The above-suggested experimental protocol (previous paragraph) could allow us to investigate this issue. For example, one may settle the same experimental design as in the study presented in Chapter III with two conditions: in one condition, the sustained

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[112] In this line of inquiry, I recently contributed to a study in which the effects of attention decrement and temporal expectations on behavioral performance and neural activity were investigated orthogonally. This study has been published as a peer-reviewed article (Derosiere et al., In Press). Please see Appendix A for the full version of this article.

attention task would be characterized by repetitive, unchanging perceptual stimulation (*i.e.*, as in the tasks exploited in the present thesis) while in the other, the patterns of perceptual stimulation provided would be changing over time and space. One hypothesis would be that, in the second condition, the over-engagement of the attention-related areas would be reduced (or even inexistent), as well as the over-excitability of the motor neural structures. The implicit assumption in this case is that the more changing perceptual stimulation is associated with a reduced (or inexistent) sensory disengagement - an hypothesis that has also to be addressed. To go a step further in this line of inquiry, one complementary investigation would consist of applying effective connectivity (*e.g.*, conditional Granger causality) analyses on brain activity data recorded during sustained attention tasks, in order to depict the potential causal relationships existing in the changes in the activity of sensory-, motor- and attention-related neural structures.

This kind of analyses (*i.e.*, Granger causality) could allow to answer another interesting question, also originating from the present work: *What is the neural origin of the increased inhibition of the sensory cortices observed with TOT?* As noted in Chapter I (see p. 113), a recent literature review (Fuentes et al., 2012) describes that the IOR process results from an active inhibition of the sensory cortices through top-down afferent signals originating from PFC and parietal cortices. However, this thesis does not claim that the IOR process is involved in sustained attention[113], but instead that the inhibitory mechanism observed in sensory cortices during sustained attention might belong to the same family of *inhibitory tagging* processes. The hypothesis of an involvement of the PFC and parietal cortices in the inhibition of the sensory cortices has thus to be tested in the context of sustained attention. Testing this hypothesis is of substantial importance. First, it would allow to figure out whether sustained attention shares similar neural correlates with the IOR process and, in this sense, would bring further support to the whole argument developed in this thesis. Second, if the PFC and parietal cortices are indeed involved in the inhibition of the sensory cortices during sustained attention, then it may explain in part the over-engagement of these structures with attention decrement. Such an observation would thus give rise to another substantial issue: what is the respective roles of both the PFC and the parietal cortices in *(i)* the sustaining of attention and in *(ii)* the inhibition of the sensory cortices during sustained attention tasks? And for that matter, is it possible that these areas are involved in both these "competitive"

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[113] The IOR process is induced in particular experimental conditions, not involved in sustained attention tasks (please see p. 113, for a related discussion).

processes (*i.e.*, inhibiting and sustaining the focus of attention) at the same time? This opens critical questions on the nature of the interactions between the different attentional networks that could occur in a given attentional task (*e.g.*, sustained attention network and attention orienting network, whose PFC and parietal areas both belong).

Several novel and relevant questions can also be identified regarding the mechanisms involved in the over-engagement of the motor neural structures with TOT. For instance, as pointed out in Chapter III (see p. 161), the respective contribution of the spinal and cortical neural activity in the TOT-related increase in CS excitability remains quite unknown. As the timing of the increase in MEP amplitude and in M1 area activity were similar in our study (Chapter III), it is sensible to hypothesize that the excitability was mainly increased at the cortical level. However, the hypothesis of an increased spinal excitability cannot be totally excluded. In addition, assuming that cortical excitability did increase with TOT, we still do not know whether this increase in cortical excitability was related to a release of inhibition and/or to an increased facilitation over the motor representation of the selected action (*i.e.*, right thumb abduction in our study). A deeper examination of these different motor neural processes seems of concern: it would not only offer a mechanistic understanding of the motor neural correlates of attention decrement; it would also allow a depiction of the neural mechanisms at the origin of the restriction in excitability characterizing motor attention[114]. Future investigation of such TOT-related motor activity changes should thus focus on the assessment of *(i)* H reflex amplitude (spinal excitability) through peripheral nerve stimulation and *(ii)* ICI and ICF processes by means of double-pulses TMS, during sustained attention RT tasks.

Following the same line of inquiry, the effect of attention decrement on the inhibition of unwanted actions remains completely unexplored. We may however assume that attention decrement also alters such inhibitory mechanisms. As discussed in Chapter IV, given the lateral inhibition interactions that underlie focused attention at the cortical and thalamic levels and that contribute to the suppression of unwanted movements, an increase in the facilitation of the selected action (*e.g.*, right thumb abduction) would result in a concomitant increase in the inhibition of unwanted actions (*e.g.*, right index flexion). In other words, the center-surround antagonism occurring in motor neural structures during focused motor attention would be sharpened with attention decrement. This represents an appealing hypothesis,

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[114] That is, such investigation could allow to depict whether the restriction in excitability observed in focused motor attention is related to the involvement of active inhibitory mechanisms or to a limitation of facilitation.

worthy of further research. An alternative hypothesis would be that the increased excitability observed in favor of the selected action extends to unwanted actions, in the form of a generic over-excitability. Investigating such issues would contribute towards a better comprehension of how attentional dysfunctions could impact behavioral flexibility and motor control processes.

Overall, this subsection demonstrates the substantial implications of the present work for future research in Cognitive Neuroscience. Given that the (sensory-motor) neural correlates of attention decrement have been relatively unexplored so far, this thesis opens several and various opportunities for future research in the field.

What's more, the knowledge acquired in the Cognitive Neuroscience part of this thesis has also direct implications in the field of Cognitive Engineering. This mirrors the numerous and strong bridges that have always existed between the two disciplinary fields since the birth of Cognitive Engineering in the early 1980s (Card et al., 1983; Norman, 1983). Specifically, our analyses of the neural correlates of attention decrement have been profitable in the field of passive BCI. It is however worth noting that our thorough study of sustained attention has a number of other practical implications, notably in the future design of human-machine interfaces. These different points are addressed in the next section.

3. Attention decrement under the scope of Cognitive Engineering

Exploiting basic scientific knowledge for the human-centered design of engineered systems: that represents one of the main aspirations of this thesis. The Part II of the manuscript provides a clear demonstration of the achievement of this goal. In the present section, I discuss the advances that the present work has offered regarding passive BCI and advocate future research directions in this field. But before focusing on this issue, I relate a number of other practical implications also arising from the knowledge acquired in the Cognitive Neuroscience part of this thesis.

3.1. Cognitive Neuroscience of attention decrement: multiple implications for Cognitive Engineering

The theory defended in this thesis leads to one major conclusion: as a by-product of evolution, human beings' perceptual systems need ever-changing sensory stimulation in order to sustain attention. Without respecting this fundamental condition, sustained attention inevitably leads to sensory-motor deficiencies, which may dramatically impact human daily activities. Given this, cognitive engineers should focus on solutions they could offer in terms of interface designs to avoid (or limit) the development of states of attention decrement in human daily activities. Some propositions of such interface designs are given below.

Prior to addressing the question of what should be designed to avoid states of attention decrement, it is of importance, as a cognitive engineer, to develop a deeper reflection about the potential drawbacks of counteracting attention decrement in some specific contexts. In the military for example, the use of tDCS has been recently proposed to boost attentional abilities during critical situations requiring sustained attention (Nelson et al., 2013; Falcone et al., 2012). The main issue that I perceive in this case is that such brain stimulation interventions might lead to the development of less flexible attentional states. The question is worth asking: do we want to produce over-focused states in the military personnel? What are the costs and benefits of counteracting attention decrement in this context? As I have previously discussed, defocusing attention over TOT might be behaviorally beneficial for human beings in certain conditions: it may allow the switching of the attentional focus from one perceptual, motor or cognitive stimulus to another. In the same manner, Robertson and O'Connell (2010) assert "*prolonged attention if overtly focused may lead to lack of detection of danger*". In this sense, attentional 'lapses' may have survival advantages in a military context, especially in critical situations. The issue is worthy of further thinking by researchers in this area of Cognitive Engineering.

In other contexts, designing artifacts allowing for the prevention of the occurrence of attention decrement may prove to be valuable. In the cases of airport screening officers and radar operators - typically known for experiencing difficulties to sustain attention in their visual screening tasks (Langner and Eickhoff, 2012), future development should consist in the design of screen displays providing higher perceptual loads. First, the use of a large screen size might induce the need to more actively switch the attentional focus from one location to another. Such design would reduce the *spatial IOR-like* process that is supposed to be stronger when visual attention remains focused on a restricted spatial area over time (*i.e.*, as occurring when using a small screen size). Secondly, constant changes in stimulus contrast and brightness might allow to reduce the *feature-based IOR-like* process that is supposed to be stronger when visual attention remains focused on an unchanging stimulus over time. Finally, one other means to modulate stimulus salience would consist in coupling visual stimulation with other sensory stimulation (*e.g.*, auditory and tactile) in a multisensory way (Matusz and Eimer, 2011). Combining these different solutions in a given interface would provide the operators' perceptual systems with a flow of ever-changing sensory stimulations and would hence limit the development of attention decrement.

In a strongly similar vein, the results of the present thesis might help the human-centered design of motor rehabilitation devices. For example, following our line of reasoning, it is sensible to assume that repeating a point-to-point movement towards the exact same location in space and with a constant movement rate would lead to a defocusing of attention from the sensory content of the task over time. In this case indeed, the visual and proprioceptive information provided by the task would be unvarying over time and space. In order to engender a further attentional engagement of patients in sensory-motor tasks (*e.g.*, stroke patients), it may be suggested to engineer devices in which they would have to explore different spatial locations at different rate with different movements (obviously in accordance with the constraints related to the pathology). The increasing use of serious gaming[115] in stroke motor rehabilitation (Burke et al., 2009) is in sympathy with this point of view: providing constant changes in perceptual stimulation to these patients allow to keep them focusing on the motor rehabilitation task over prolonged periods of time.

Speaking of pathology, our findings might also have implications for the future design of active BCIs which, for the most part, involve sustained attention. One major issue of these systems is the cognitive demand that they put on the patients. In fact, a qualitative analysis of active BCIs leads to the observation that the high "cognitive demand" associated with their use is mainly caused by a lack of changes in perceptual stimulation provided to the user by the

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[115] Serious gaming refers to the use of video games to rehabilitation purposes.

interface. Accordingly, using such active BCIs leads to attention decrement and, as attention decrement is associated with changes in brain activity, supervised classifiers encounter then strong difficulties to detect the intention of the BCI user[116]. This is for example what happens in the use of the P300 speller (*e.g.*, Kaper et al., 2004). Using a P300 speller interface requires the patient to focus on one letter out of a screen displaying the whole alphabet in a grid. Flash light are displayed at a certain rate in the rows and columns of the grid, and the patient's EEG activity is recorded. Each time a flash occurs over the letter selected by the patient (*i.e.*, on which attention is focused), a P300 wave is elicited. Once the flashes are repeated a sufficient number of times, the system detects which letter the patient is focusing on. By doing so, the patient is able to spell words and sentences, one letter after another. What is worthy of note, however, is that the flash light features are absolutely unchanging over time in these systems, which is really likely to contribute to the development of attention decrement. One may assume that the development of attention decrement during the use of a P300 speller interface could be reduced if the color, the color contrast, the brightness and the presentation rate of the flash light were all varying over time. This suggestion involves further research to define the effect of such changes in perceptual stimulation on the P300 features. In a general manner, the three different suggestions of interface designs described here (*i.e.*, screening operators' visual interfaces, motor rehabilitation devices and P300 speller BCIs) necessitate the concomitant realization of Cognitive Neuroscience investigations and Cognitive Engineering developments. In this line, an intriguing question to address in the future of both Cognitive Neuroscience and Cognitive Engineering investigations regards how human beings' perceptual and cognitive abilities would adapt, on a long-term scale, to the design of such perceptually challenging interfaces. As Steven Johnson (2010) brilliantly remarked "*our thoughts shape spaces [but]*[117] *our spaces return the favor*". The increasing stimulation provided by our technologies might indeed condition, fashion, define the future of human cognition.

There are situations where technology cannot be used as a means to provide changes in perceptual stimulation. This is the case when attention decrement occurs in a task where the perceptual stimulation is not provided by an electronic device (*e.g.*, the screen for screening operators or P300 users) but by other sources of sensory stimulation (*e.g.*, the instrument for the beginner musician, the patient's brain for the neurosurgeon, the road for the car and truck

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[116] Given that attention decrement is associated with changes in brain activity, the features of the brain data to be classified are different from the features of the brain data exploited for the machine learning step.

[117] Brackets added.

drivers, or the railway for the train driver). In the case of driving, alternative solutions have been identified to provide changes in perceptual stimulation as when "*civil engineers build curves in highways across flat land where there is no geographical or geological need to do so*" (*i.e.*, according to the terms exploited by Robertson and O'Connell, 2010). The possibilities of modulating the level of perceptual stimulation remain however relatively limited in these situations (*i.e.*, in music playing, surgery operation, or driving). The use of passive BCI seems thus of substantial interest in the context of such sensory-motor activities. Instead of anticipating and limiting the development of attention decrement, the aim is then to detect its occurrence and provide feedback to the human operator.

3.2. Detecting attention decrement through NIRS-based passive BCI[118]

We are still at the dawn of the development of efficient passive BCI. On the one hand, EEG-measured electro-cortical activity has been recently shown to allow the classification of different attentional states (*e.g.*, Shen et al., 2008; Stikic et al. 2011; Trejo et al., 2007). On the other hand, NIRS-measured cortical hemodynamics has latterly proven to enable the classification of affective states (Girouard et al., 2013; Luu and Chau, 2009; Peck et al., 2013; Tai and Chau, 2009) and of different levels of cognitive workload (Coffey et al., 2012). The main contribution of this thesis has consisted in testing the potentiality of exploiting NIRS-measured cortical hemodynamics to classify two different attentional states during a sustained attention task. Our results support the feasibility of developing NIRS-based passive BCI to detect attention decrement occurrence.

Beyond this main contribution, our data-driven analysis has revealed intriguing results if one considers the current context of NIRS investigation in neuroergonomics, a brief review of which has been provided in Chapter VI. The verdict of this review was crystal-clear: the PFC area was considered as a "gold location" by NIRS investigators of the field. We clearly demonstrate in this thesis that it should not be the sole area to focus on: the right parietal area allowed us to classify two attentional states with a better accuracy than the PFC. The intuition reported early in Chapter VI was that "by investigating PFC activity only, NIRS studies in

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[118] This section provides a brief discussion of our contributions in the field of passive BCI. The aim is to avoid the redundancy with the discussion of the different technical points that have already been provided in the Part II of the manuscript.

neuroergonomics probably missed other relevant information conveyed by activity in other task-related cortical areas. [and that] this lack could *(i)* impede the development of a comprehensive account of the cortical correlates of human-machine(s) interactions and *(ii)* decrease classification accuracy of any NIRS-based real-time classification of cognitive states" (see p. 196). Even if setting NIRS probes over the PFC scalp area indeed presents technical advantages (discussed p. 198), cognitive engineers in the field of neuroergonomics should reconsider whether it is worth completely blinding themselves to changes in the activity of other brain structures.

The finding that the right parietal area activity represents a relevant input to passive BCI could have not been demonstrated without the reflection developed in the Cognitive Neuroscience part of the manuscript. It is following a critical analysis of the neural correlates of focused attention, sustained attention and attention decrement that we decided to investigate the potentiality of using *both* the parietal area and the PFC activities as inputs to passive BCI. It is worth highlighting that the data-driven analyses performed following this knowledge-driven decision returned the favor. The results obtained then may be indeed useful to develop deeper thinking about the respective contribution of the PFC and the right parietal areas to sustained attention and attention decrement. On the whole, the LOOCV procedure exploited in our study shows that generalization performance was better across subjects based on right parietal area activity than on PFC activity. This better generalization might have two main origins which are not without consequences for our understanding of sustained attention and attention decrement. First, given that our supervised classification analyses were based on the changes in NIRS signals amplitude over time, the observed difference in generalization performance might be the consequence of higher changes in cortical activity in the right parietal area as compared to the PFC over TOT. In the feature space, the two points clouds representing the first and last ten minutes of the task would have been then more distinguishable using the signal from the right parietal area since they would have been more distant from one another (*i.e.*, in terms of Euclidian distance). This finding would signify that the over-engagement of the attention-related areas - which is supposed to reflect the need for re-focusing attention on the sensory content of the task - would be more pronounced in the right parietal area than in the PFC. However, the results of our study in Chapter III (Figure 3.4., p. 157) depict similar average amplitude changes for the right parietal area activity and for the PFC activity. We need thus an alternative interpretation. Another explanation is that the observed difference in generalization performance may have resulted from the fact that the patterns of activity in the right parietal area were more reproducible across subjects than those of PFC activity. Such a result would be of substantial importance: it would imply that the PFC activity is more likely to be variable from one individual to another during an attentional task and could, somehow, represent a signature of individuality in human cognition. In this sense, exploiting PFC activity for generalization purposes is problematic, a conclusion which is not positive for PFC-centered investigation in the field of passive BCI. The results of our study in Chapter III (Figure 3.4., p. 157) seem to support the assumption of a higher inter-subject variability in PFC activity as compared to right parietal area activity during sustained attention. One question that arises from this observation is whether the inter-subject variability in PFC activity could be handled through the development of appropriate classification methods. This kind of issue is one of the future avenues for research in Cognitive Engineering.

3.3. Future avenues for research in Cognitive Engineering

"*A good idea is a network*" claimed Steven Johnson (2010). In (cognitive) engineering, each novel development, each new design, each innovation creates a number of new questions, such that the latest advances and the future ones form a tree-like pattern together. Following this reasoning, while the Cognitive Engineering part of this thesis has addressed a number of issues that were identified in the field, it also reveals a number of other issues and leads to many ideas for future investigation.

One such issue has been briefly mentioned in the previous subsection and concerns the inter-subject variability encountered in brain data in BCIs. Variability is actually ubiquitously present in biology (Reinhold and Engqvist, 2013) but when one has the aim of precisely discriminating one psycho-physiological state from another based on biological signals, this represents a palpable issue. So far, the problem has been essentially addressed in the field of active BCI. Some solutions have been put forward to resolve this issue both in the cases of EEG- and NIRS-based active BCI, such as *(i)* new data processing and pattern classification methods (Nicolas-Alonso and Gomez-Gil, 2012); *(ii)* semi-supervised SVM classifiers (Li et al., 2008); *(iii)* adaptive classifiers based on multiple-kernel SVM (Abibullaev et al., 2013); or *(iv)* models of brain signals variability in order to generate homogeneous groups of data sharing similar spatial distributions within the feature space (Dalhoumi et al., 2014[119]). Future investigation in the field should address the question of the transferability of these different methods to both EEG- and NIRS-based passive BCIs. In the case of NIRS-based passive BCI, the issue is of importance: it might allow us to improve classification performance while exploiting PFC activity to detect attention decrement. One might then be able to keep the technical advantages of setting NIRS probes over the frontal scalp area, while reducing the negative impact of this scalp location in terms of classification accuracy. However, it is worth remembering that PFC-centered investigation can be detrimental as it can lead to missing relevant information conveyed by activity in other task-related cortical areas. In the future, each method tested on NIRS-measured PFC signals must be, when relevant, tested on signals obtained from other task-related cortical area. Consequently, for the purpose of detecting attention decrement, the use of classification methods dealing with inter-subject variability should be tested on NIRS-measured right parietal area activity as well.

Another question to address in the development of passive BCI, also related to the issue of generalizability, concerns whether a model built based on brain data recorded in a certain attentional task would enable the classification of different attentional states in other conditions. In this thesis, the learning and test steps were performed on NIRS data recorded during the same specific task: a thirty minutes duration sustained attention visual RT task. The problem in this case is that the model built can be actually strongly specific to the task realized by the subjects, leading then to a form of over-fitting. Future studies in the field should thus undertake NIRS measurements of cortical activity during different sustained attention tasks and subsequently investigate the capability of detecting attention decrement in one task based on a model trained with NIRS data recorded in another task. This kind of question has been already addressed in the context of EEG-based passive BCI (Johnson et al., 2011) and should represent a priority for future research in NIRS-based passive BCI. Following this line of inquiry, a relevant question to address would be whether some specific attention-related cortical areas allow for a better generalization over different sustained attention tasks as compared to others. In other words, is there a consistent cortical signature of attention decrement, observable over several attentional tasks in a reproducible manner? And what are, on the other hand, the cortical areas showing more task-dependent changes in

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[119] This investigation was performed by our team and published as:
Dalhoumi S, Derosiere G, Dray G, Montmain J, Perrey S. (2014). Graph-based transfer learning for managing brain signals variability in NIRS-based BCIs. *Proceedings of the 15th International Conference on Information Processing and Management of Uncertainty.* Please see Appendix B for the full text version of this article.

activity? These questions are not only significant for the future development of efficient passive BCI, but also for our understanding of sustained attention and attention decrement.

Our results (Chapter VII) raise also the question of the relevance of combining several NIRS variables together as features in the supervised classification procedure. Feature selection actually represents an important aspect of supervised classification analyses and here, future research should be conducted on this issue in the field of NIRS-based passive BCI which is just burgeoning. In this thesis, we observed that combining signals from the PFC and from the right parietal area in our classification analyses did not further increase classification performance, in fact, it led to a decrease in accuracy in some cases (*e.g.*, as compared to when exploiting signals from the right parietal area exclusively). Similar findings were observed while combining [O_2Hb] and [HHb] variables as features in our classification analyses in contrast to when exploiting the [O_2Hb] variable only. These findings can be related to the *curse of dimensionality* phenomenon (Bellman, 1967) which basically describes that, with a fixed number of learning samples the predictive power of a given model diminishes as the number of dimensions of the feature space increases[120]. Given this, a number of methods have been proposed in the literature to resolve the issue of feature selection. The aim of these methods is usually to minimize the mutual information provided by the different selected features, as for example through maximal dependency, maximal relevance or minimum redundancy methods (Peng et al., 2005). Thus, while our data-driven approach created pilot results regarding the NIRS variables offering the best classification performance in the purpose of detecting attention decrement, future investigation should apply feature selection methods to confirm, infirm, or complement these pilot results. Here again, the bridges with Cognitive Neuroscience are manifest: depending on which features are selected (*e.g.*, NIRS signals from a given, particular cortical area) one may then be able to generate conclusions about the relationship between each cortical area's activity and behavioral performance[121].

The last three identified objectives (*i.e.*, developing methods dealing with inter-subject variability, testing the models' generalizability from one task to another and determining the most relevant NIRS variables based on feature selection methods) are part of an overall first step for future research in the field. The next stepping stone would be to evolve from binary to multi-classes classification systems, allowing discrimination of more than two attentional

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[120] This effect is also known as the Hughes effect (Hughes, 1967).

[121] For example, if the NIRS-measured right LPFC's activity is selected as feature while the left LPFC's activity is not, then we may conclude that the right LPFC's activity allows to better predict attention decrement and accordingly that this area has a more substantial role in the development of the phenomenon.

states. As described in Chapter V, the initially developed *non-brain-based* cognitive state tracking systems allowed discrimination of sleepy from attentive states (*i.e.*, in the context of driving). The evolution from these systems towards EEG-based cognitive state tracking systems (*i.e.*, passive BCI) has allowed the gain of a finer discriminative power, and this evolution has been characterized by two degrees of advancement. The first step has consisted of observing changes in behavioral performance during sustained attention tasks in order to discriminate *two* different attentional states (*e.g.*, Trejo et al., 2007), while the second one has consisted of increasing the number of classes to be discriminated (Shen et al., 2008). In this line of inquiry, while the present thesis has contributed to address the first step in the context of NIRS-based passive BCI (*i.e.*, binary classification of attentional states), future investigation should consider the possibility of developing NIRS-based multi-classes classification systems.

Finally, the ultimate step on a longer time scale would be to combine EEG- and NIRS-based passive BCI together, in a multimodal manner. As I stated in Chapter V such a multimodal fusion has been shown to be beneficial in terms of classification performance in the case of active BCI (*e.g.*, Leamy and Ward, 2010). However, to my eyes, multimodal fusions represent another level of challenge for future research in the field and this challenge should be taken only once the several issues identified in NIRS-based passive BCI have been addressed.

4. Concluding Remarks

The multidisciplinary study presented in this thesis provides a deeper insight into the neural underpinnings of attention decrement and demonstrates how this knowledge can be exploited to develop devices which allow either the prevention of the occurrence of the phenomenon, or warn of its presence. While some questions have been answered, a number of others have been raised, both in the field of Cognitive Neuroscience and Cognitive Engineering. Our understanding of the phenomenon is still only partial and accordingly, the currently designed technological devices are not optimized for the human sustained attention system. The thorough discussion developed in this chapter emphasizes the clear interest in further developing bridges between Cognitive Neuroscience and Cognitive Engineering to address the issue. The routes offered by these bridges should be bi-directional. In the future, Cognitive Neuroscience investigations should be realized hand in hand with Cognitive Engineering developments with the goal of disentangling the neural correlates of attention decrement.

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Appendix A

Appendix A is comprised of three articles arising from this thesis. Some of the results of these three studies have been presented in the manuscript. A brief description of the contribution of these three articles to the thesis is provided below.

Article 1

Published as: Mandrick K, **Derosiere G**, Dray G, Coulon D, Micallef JP, Perrey S. (2013). Prefrontal cortex activity during motor tasks with additional mental load requiring attentional demand: a near-infrared spectroscopy study. *Neuroscience Research,* 76, 156-162.

Description of the contribution to this thesis: the behavioral data obtained in this study are exploited in Chapter I as an illustration of Kahneman's resources theory (please see section 1.2.3. Attention resources-based theories, pp. 40-47). These results allowed me to demonstrate how the resources theory can be supported by behavioral data in the context of divided attention.

Article 2

Published as: **Derosiere G**, Farrugia N, Perrey S, Ward T, Torre K. (In Press). Expectations induced by natural-like temporal fluctuations are independent of attention decrement: Evidence from behavior and early visual evoked potentials. *NeuroImage, doi: 10.1016/j.neuroimage.2014.09.015.*

Description of the contribution to this thesis: a brief description of this study has been provided in the foreword section of Chapter II (please see p. 119). In this study, participants came twice to the laboratory to perform a sustained attention task under two different conditions. The two sustained attention tasks performed differed in the structures of the presented ISI. In one condition, the ISIs were randomly distributed to impede expectation effects (*i.e.*, WN condition) while in the other condition, the ISI exhibited long-term correlations, inducing temporal expectations. We thus manipulated TOT-related changes in attention and temporal expectations orthogonally and subsequently assessed how it affected behavioral performance and several components of the VEP. In Chapter II, I exploited the EEG and behavioral data from the WN condition and addressed the issue of the sensory neural correlates of attention decrement.

Article 3

Published as: **Derosiere G**, Dalhoumi S, Billot M, Perrey S, Ward TE, Dray G. (2013). Classification of NIRS-measured hemodynamics of the cerebral cortex to detect lapses in attention. *Proceedings of the 16th International Conference on Near-InfraRed Spectroscopy.*

Description of the contribution to this thesis: this publication represents a pilot study on the potential of exploiting NIRS-measured attention-related areas' activity to detect attention decrement. The idea was to test whether, based on PFC data exclusively, we could reliably distinguish two attentional states using supervised classification analysis. In this way, this study is preliminary to the deeper analysis performed in the study presented in Chapter VII.

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Prefrontal cortex activity during motor tasks with additional mental load requiring attentional demand: A near-infrared spectroscopy study

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ABSTRACT

Functional near-infrared spectroscopy (fNIRS) is suitable for investigating cerebral oxygenation changes during motor and/or mental tasks. In the present study, we investigated how an additional mental load during a motor task at two submaximal loadings affects the fNIRS-measured brain activation over the right prefrontal cortex (PFC). Fifteen healthy males performed isometric grasping contractions at 15% and 30% of the maximal voluntary contraction (MVC) with or without an additional mental (i.e., arithmetic) task. Mental performance, force variability, fNIRS and subjective perception responses were measured in each condition. The performance of the mental task decreased significantly while the force variability increased significantly at 30% MVC as compared to 15% MVC, suggesting that performance of dual-task required more attentional resources. PFC activity increased significantly as the effort increased from 15% to 30% MVC ($p < .001$). Although a larger change in the deoxyhemoglobin was observed in dual-task conditions ($p = .051$), PFC activity did not change significantly as compared to the motor tasks alone. In summary, participants were unable to invest more attention and effort in performing the more difficult levels in order to maintain adequate mental performance.

1. Introduction

Interaction between motor and mental tasks was suggested to have a central origin. As argued by Baddeley (1986), the ability to perform tasks simultaneously is one of the most important roles of the central executive functions with respect to dorsolateral prefrontal cortex (PFC) region (Funahashi, 2006). PFC is an area well-known to be involved in a number of tasks ranging from mental (e.g., computation) to physical (e.g., handgrip task, gait balance) demands (Holtzer et al., 2011; Ward and Frackowiak, 2003). Recent neuroimaging research has suggested that the control of the attentional process during dual-tasks requiring divided attention is associated with the activation of the (bi)lateral PFC (Atsumori et al., 2010; Holtzer et al., 2011; Stelzel et al., 2009; Tachibana et al., 2012). Studies on the cerebral correlates of number processing (Dehaene and Cohen, 1997; Houdé and Tzourio-Mazoyer, 2003) and of hand motor abilities (Binkofski et al., 1999) pointed out the importance of an overlapping prefrontal and intraparietal circuit; the frontal region being more related to retrieval of arithmetic calculation (Dehaene and Cohen, 1997). A simple motor task such as handgrip activity that is commonly experienced in daily life but performed under dual-task conditions while performing a semantic task, may be a meaningful indicator of functional abilities that replicate activities of daily living. However, no study has clearly distinguished the extent of frontal activation resources required to perform a moderately intense mental task (e.g., an arithmetic task) whilst performing submaximal grasping tasks.

One current method, with the potential to investigate brain cortical (de)activation for measurements in a natural setting, is functional near-infrared spectroscopy (fNIRS). fNIRS is an optical imaging method that measures the concentration changes in both oxygenated and deoxygenated hemoglobin (HbO_2 and HHb, respectively) and appears suitable to assess the relationship between cortical activation and hemodynamic response. We recently showed during a handgrip task that the fNIRS-measured activation of the primary motor area contralateral to the hand involved in the task was positively related with the level of submaximal forces (Derosiere and Perrey, 2012). This result agrees with findings from Dai et al. (2001) who investigated the right

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Abbreviations: PFC, prefrontal cortex; NIRS, near-infrared spectroscopy; fNIRS, functional near-infrared spectroscopy; MRI, magnetic resonance imaging; MVC, maximal voluntary contraction; STAI, State-Trait Anxiety Inventory; RPE, rating of perceived exertion; VAS, visual analog scale; ANOVA, analyses of variance; DP15, perceived difficulty of the task; EEG, electroencephalography.

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PFC area activation with functional magnetic resonance imaging (MRI). However, to the best of our knowledge, it remains unknown whether the production of several levels of submaximal force during a handgrip task requires more cortical resources than that without additional mental task. As outlined above, additional processing requirements could be reflected in terms of increase in brain activity during dual-task situations.

Therefore, this study aimed to examine how a mental task in combination with performance of a grasping task that ranged from low to moderate levels of effort influences the PFC activation. We hypothesized that a greater fNIRS-measures activation of the right PFC occurs during the combined mental-motor task (i.e., dual-task) as compared to the motor task alone, as high attention demand is required to distribute and control the allocated resources in the cortical region when performing such a paradigm (Holtzer et al., 2011; Nebel et al., 2005; Stelzel et al., 2009; Tachibana et al., 2012). Moreover, we hypothesized that producing a high level of force increases the attentional demand as demonstrated through a decrease in performance of an arithmetic task (Nebel et al., 2005).

2. Materials and methods

2.1. Participants

Fifteen healthy undergraduate and graduate students took part in the present study (means ± SD; 28.3 ± 6 years; 178 ± 6.3 cm; 75 ± 11.8 kg). We recruited only male subjects to avoid differences between both sexes with respect to cortical oxygenation responses (Tanida et al., 2004; Yang et al., 2009). The participant's history and physical examination were negative for known injuries, neurological, endocrinological and cardiovascular diseases or medication, which might affect brain function. Each volunteer provided a written informed consent prior to enrolling in this study. All procedures were approved by the local ethics committee (CPP number 2010-11-05) and complied with the Declaration of Helsinki for human experimentation.

2.2. Experimental design and procedures

Each subject was required to attend the laboratory on 2 occasions. During the initial visit, participants were screened regarding the study exclusion/inclusion criteria. Training was given on the motor and mental tasks and the compliance requirements for the following testing session were explained. Subjects were requested to assess at this occasion their perceived difficulty of the mental task using the DP15 scale (Delignieres et al., 1994). The DP15 scale consists of a 15-point category scale, with 7 labels, from 2 (extremely easy) to 14 (extremely difficult), symmetrically placed around a central label 8 (somewhat difficult). During the familiarization session, all participants perceived the task close to "somewhat difficult" (average DP15 = 7.72 ± 0.98). Based on this specific scale, the load of the mental task was of a moderate level.

On the second visit, 2 or 3 days apart, subjects participated in a block design paradigm during a single testing session. Subjects were seated comfortably on a chair in a dimmed room and in front of a LCD monitor with their eyes open throughout the measurement. The monitor was used to display the force exerted by the grasping movement. The testing session comprised an isometric handgrip task at two different levels of loading with or without an additional mental task. Each task lasted 60 s, followed of a 90 s resting period to allow the hemodynamic activations with fNIRS to return to a zero baseline value at the first stimulus onset. Subjects were instructed to give the best performance during both tasks (i.e., motor and mental). Visual cues indicated to the subjects the task and rest periods as prompted on the screen. Subjects completed three repetitions of each task in a randomized order. Immediately after the performance of each task, subjects were requested to indicate their level of perceived stress with a 100-mm visual analog scale (VAS). The VAS scale ranged from 0 to 10 corresponding to endpoints labeled as "not at all stressed" to "very stressed". The stress to the subjects was defined as similar that of experienced during a physical perturbation (e.g., sweating, shivering, heat, increase in heart rate) (Johnson, 2001). Moreover, rating of perceived exertion (RPE) was evaluated by the Borg scale (from 6 to 20) (Borg, 1970) at different epochs throughout the study. Note that at the beginning and end of the testing session the acute affective states were assessed with the State-Trait Anxiety Inventory (STAI, form Y-A) questionnaire (20 items with a four-point Likert-type scale response) (Spielberger et al., 1970). The entire testing session lasted approximately 70 min. The timelines and running order of the testing session (block design) are presented in Fig. 1. All the physical signals (fNIRS and force, see below) were measured at 25 Hz in a synchronous manner using a Biopac MP100 system (Biopac Systems, CA, USA).

2.3. Motor task

Subjects performed grasping tasks with their non-dominant hand. According to Yoon et al. (2009), we chose the non-dominant arm to minimize the variability between subjects that may occur due to differences in regular daily activities performed with the dominant arm. Subjects were classified as right-handed using the Edinburgh Questionnaire (Oldfield, 1971). The task consisted of two steps. First, subjects performed three 5 s efforts of maximal voluntary contraction (MVC), with at least 30 s rest period between contractions. The peak torque of the three contractions was averaged then retained to express target force levels (in % MVC). Second, subjects were instructed to quickly produce and maintain force levels for 60 s at two different submaximal workloads (i.e., 15% and 30% MVC) by matching the target force displayed on the monitor as close as possible. Low and moderate levels of handgrip task (i.e., 15% and 30% MVC, respectively) were chosen to avoid restriction in muscle blood flow, that could induce in turn induce adverse cerebrovascular responses due to augmented sympathetic activation (Vianna et al., 2012). The left arm was naturally extended to ~180° at the elbow to avoid the effects of any possible compensation during the motor task. The handgrip dynanometer was held in a horizontal position in order to exert force in the vertical plane. A force transducer (Captels, Saint-Mathieu-de-Treviers, France) was calibrated prior to measuring force production continuously during the testing session. Moreover, the force output signal allowed us to compute the quantitative grasp force magnitude and variability. Force variability was indexed with the force signal as standard deviation (SD) during the steady state portion of the task (i.e., steadiness). SD value quantifies how well the output of the muscle controller sustains a mean force value over a stationary time period.

2.4. Mental task

The proposed mental arithmetic task is an well-established psychological technique for evaluating mental workload (Critchley et al., 2000; Noteboom et al., 2001). Subjects were requested to perform 60 s of mental arithmetic consisting of sequential mathematical calculations (Sakatani et al., 2010; Tanida et al., 2004, 2007, 2008). The mental task began with the subtraction of a two-digit number from a four-digit number (e.g., 1766 – 17 = ? – 14 = ? – 19 = etc.) as quickly and accurately as possible, and continued throughout the 60 s interval with successive subtractions of the number from the result of the previous subtraction. After each response, the experimenter repeated the last

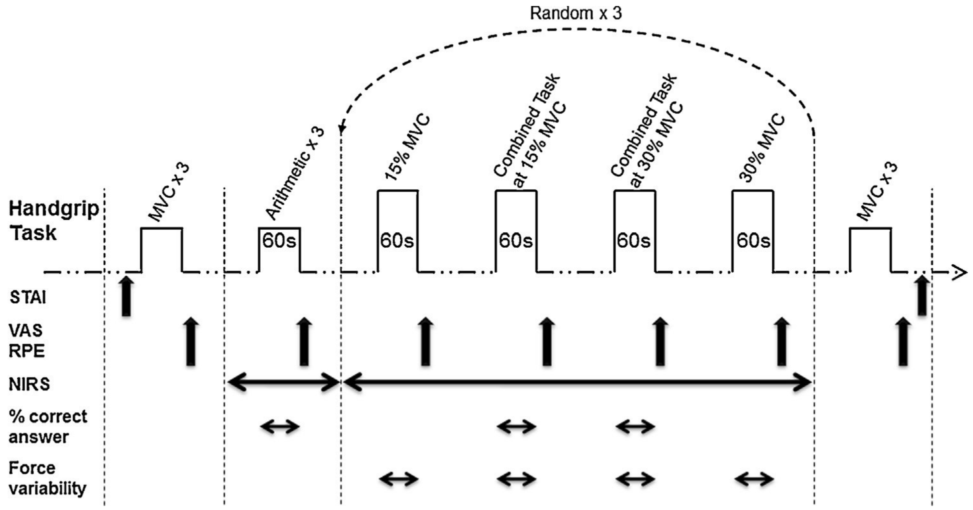

Fig. 1. Experimental protocol. Upper: the order of testing session with the different tasks. Each task lasted 60 s followed by 90 s rest period. Maximal voluntary contractions (MVC) were separately monitored at the start and at the end of the experimental session. A control condition for the mental task alone (i.e., arithmetic task alone) was performed before the analyzed experimental session. The different conditions tested corresponded to a handgrip task at different levels (i.e., 15% or 30% of MVC) with or without an additional mental task. Lower: horizontal arrows show the recording of hemodynamic activity using near-infrared spectroscopy (NIRS), the measurement of % correct answers and the force variability. Vertical arrows show when the State-Trait Anxiety Inventory by State (STAI-S) form Y-A, visual analog scale of stress (VAS) and rating of perceived exertion (RPE) were assessed for each block.

four-digit number found by the subject and proposed another two-digit number to subtract. About ten arithmetic operations a minute were carried out on average for each subject. The number of arithmetic tasks completed correctly was recorded and expressed in % of the total number of the proposed arithmetic tasks for each force level. Subjects underwent a practice session before data collection to ensure familiarization with this mental task scheme, but with different numbers to avoid any learning effect.

2.5. NIRS apparatus and PFC localization

An NIRS instrument (NIRO-300, Hamamatsu Photonics K.K., Japan) measured the time course of relative changes in the concentrations of [HbO_2] and [HHb] at time resolution of 0.5 s. Hemodynamic changes in HbO_2 and HHb were calculated by means of a modified Beer–Lambert law with the proprietary software and reported as relative changes in concentration (μM.cm). An emitter-optode pair (that includes three separate photo-detectors and a light emitter) with an inter-optode distance of 50 mm was placed at the midpoint between Fp2-F4 landmarks of the international EEG 10–20 system electrode placement (Jasper, 1957). The international 10–20 system is commonly used for placement with good reproducibility. Tanida et al. (2007) have previously shown with MRI that this location overlies the dorsolateral and frontopolar areas of the PFC. The probe holder was maintained with a special black semi-rigid rubber holder set in a homemade headband and covered by a thin aluminum sheet for light protection (Perrey, 2008). To reduce artifact, subjects were asked to minimize head and body movements and instructed to breathe gently and regularly. The fNIRS data output was event timestamped at the start of each task condition to ensure that measurements corresponded to the relevant epoch of task.

2.6. fNIRS analysis

Pre-processing and processing of NIRS signals were performed off-line using a customized code implemented in Matlab 7.0 software (The Mathworks Inc., MA, USA). Mostly, both [HbO_2] and [HHb] provided sufficient information about regional hemodynamic changes and are recognized as the main relevant parameters to depict brain activation (Perrey, 2008). Indeed, using fNIRS signal measurements, neural activation is typically expressed as an increase in [HbO_2] accompanied with a decrease in [HHb] (Gervain et al., 2011). Hence, as proposed by Obrig and Villringer (2003), it is necessary to routinely report both parameters. fNIRS data were first low-pass filtered using a cut-off frequency of 0.1 Hz to smooth the curves and avoid higher frequencies due to movement, respiration and heart beats. In the present study, we used a time series analysis technique (i.e., amplitude-based approach) to assess and discriminate the cortical activation changes during each functional task compared to a reference point recorded just at the onset of the first task. During the rest period between tasks, subjects were instructed to (i) stay relaxed, (ii) keep their eyes open, and not control their mental activity in any particular way while brain activation was absent (Gusnard and Raichle, 2001).The amplitude-based approach quantifies the average concentration change of [HbO_2] and [HHb] to pre-stimulation state across conditions (Gervain et al., 2011). Hence, we calculated the relative concentration (Δ) for [HbO_2] and [HHb] by subtracting the level obtained at the resting state (last 10 s of the rest period) from the activation period (last 10 s of the task) for each trial (Holper et al., 2009).

2.7. Statistics

All statistical analyses were performed with Statistica software (StatSoft France 2006, STATISTICA, version 7.1, France). All data were examined for normality and homogeneity using Shapiro–Wilk and Levene tests, respectively. All variables were normally distributed permitting the use of parametric statistical analyses. Pre and post comparisons of MVC and STAI scores were carried out with Student's paired *t*-test. Mental performance was analyzed by one-way (additional task) repeated measures univariate analyses of variance (ANOVA). Force variability, VAS and RPE scores for subjective perceived stress and exertion, respectively were statistically tested by a two-way ANOVA (handgrip force level with or without additional mental task). As regards the fNIRS data analysis, we conducted a two-way ANOVA comprising handgrip force level (15% and 30% MVC) and additional mental task (with and without). Whenever necessary, LSD Fisher post hoc test was conducted to explore interaction effects.

All data values were reported as means ± SD within the text and +1 SD on the figures. A significance level of $p < .05$ was used for all comparisons. For further statistical analysis, we utilized an effect size (d). Cohen (1988) defined effect size (d) as the mean change score divided by the standard deviation of change. Generally, it is agreed that effect size is not important if $d < .20$, small $\geq .20$, medium $\geq .50$, large $\geq .80$ and very important when it exceeds 1.0.

3. Results

3.1. Performance indicators

The mental performance of the arithmetic task changed significantly according to the conditions ($F = 4.43$; $p < .05$). Post hoc analysis test indicated that the % of correct answers declined ($p < .01$; $d = 0.41$) for the combined task at the highest force level (performance ∼72% at 30% MVC) compared to the control condition performed alone (that corresponded to ∼80% of correct calculations). No significant effect was observed at 15% MVC (performance ∼77%) as compared to the control condition ($p > .05$). However, the decrease of mental performance during the combined task at 15% MVC as compared to at 30% MVC was close to being statistically significant ($p = .06$; $d = 0.30$).

Regarding the SD of force level, the two-way ANOVA revealed a significant interaction effect (force level × additional task) ($F = 5.12$; $p < .05$). Post hoc analysis exhibited an important difference by ∼83% between 15% MVC and 30% MVC ($d = 1.57$). The SD of force at 30% MVC was greater with an additional arithmetic task compared to without (SD value of 0.56 ± 0.27 and 0.45 ± 0.19, respectively; $p < .01$; $d = 0.47$) but did not change significantly at 15% MVC (SD value of 0.27 ± 0.06 and 0.28 ± 0.07, respectively; $p > .05$).

As expected, based on MVC changes, no physical fatigue occurred throughout the testing protocol (36.8 ± 11 kg versus 33.8 ± 12 kg; $t = 1.39$; $p > .05$).

3.2. Behavioral perceptive responses

The STAI Y-A score was unchanged between the beginning and the end of the protocol (28.5 ± 5 versus 28.8 ± 6, respectively; $t = 0.43$; $p > .05$). The RPE values increased significantly with the force levels ($F = 108.7$; $p < .001$; Fig. 2). The mean scores of RPE were 9.5 ("light") at 15% MVC and 13.7 ("somewhat hard") at 30% MVC. When compared to values at 15% MVC, the effect size reached $d = 2.43$ at 30% MVC. However, no effect was evident in RPE during tasks with additional mental load ($F = 0.11$; $p > .05$) as well as for the interaction effect. Stress level scores (VAS) were significantly affected by both motor ($F = 23.5$; $p < .001$; $d = 0.54$) and mental ($F = 21.9$; $p < .001$; $d = 0.79$) tasks, whereas the interaction effect was not significant ($p = 0.31$; Fig. 2). Note that the higher VAS scores (2.6 at 15% MVC and 3.4 at 30% MVC) occurred during the dual-task condition.

3.3. fNIRS responses

The typical fNIRS hemodynamic pattern (i.e., an increase in [HbO$_2$] associated with a concurrent decrease in [HHb]) was found in a large sample of subjects and especially when the handgrip force production was high (Fig. 3). This oxygenation pattern was also observed for the control condition where the arithmetic task was performed alone (see Fig. 3).

It is noteworthy that after analyzing 225 measurements of fNIRS variables (15 subjects × 5 conditions × 3 trials), the percent of increase in activation pattern was 51%. The remaining pattern was a so-called "deactivation" pattern (i.e., inverse fNIRS response; about 13%) or no evident changes (i.e., absence of increase/decrease in any hemoglobin species between rest and stimulation periods; about 36%). NIRS signals revealed a main effect of the force level on fNIRS responses ($p < .01$, Fig. 4), but the main effect of the superimposed mental load and the interaction effect were not significant ($p > .05$). Post hoc analyses indicated that the changes in [HbO$_2$] showed a significant higher response ($F = 25.4$; $p < .001$) where the effect size reached $d = 0.97$ at 30% MVC compared to 15% MVC. The results obtained from [HHb] were similar ($F = 21.5$; $p < .001$; $d = 0.86$). One striking result from the [HHb] data was that the main effect of additional mental task was close to be significant ($F = 4.37$; $p = 0.051$; $d = 0.42$).

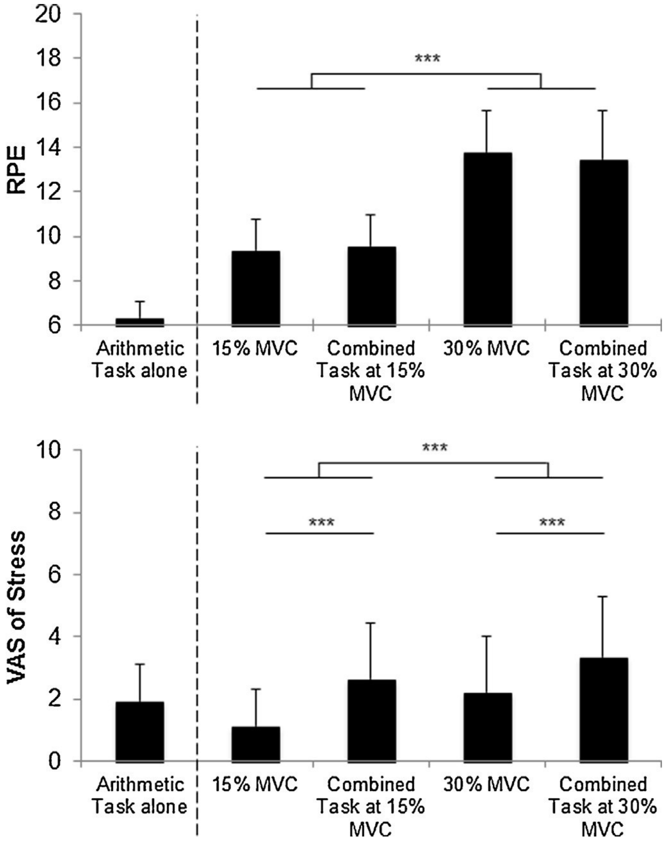

Fig. 2. Perceptive responses (mean + SD) during the two submaximal loadings (handgrip levels at 15% and 30% MVC) with and without additional arithmetic task and the control condition (mental task alone). (A) The histogram shows the mean score of rating of perceived exertion (RPE). (B) The histogram displays the stress level score evaluated by visual analog scale (VAS). MVC, maximal voluntary contraction; $^{***}p < .001$.

4. Discussion

This study aimed to examine how an additional demanding mental task during motor task of two different submaximal loadings affects the fNIRS-measured PFC activation in healthy subjects. Particularly, we hypothesized that performing a combined moderate mental-motor task would influence the level of brain activation measured by fNIRS over the right PFC, due to expected higher demands resulting from distribution for allocated resources. One of the most salient findings was that the combined mental-motor task activates the right PFC region (Atsumori et al., 2010; Holtzer et al., 2011; Stelzel et al., 2009) that is similar to that of during a single motor task. Noteworthy is that PFC displayed relative activation with regards to the submaximal force production in the context of the present study.

It is still unclear whether the increase of the attentional resources when performing a submaximal level of force with additional mental loading is associated to an increase of cortical activity

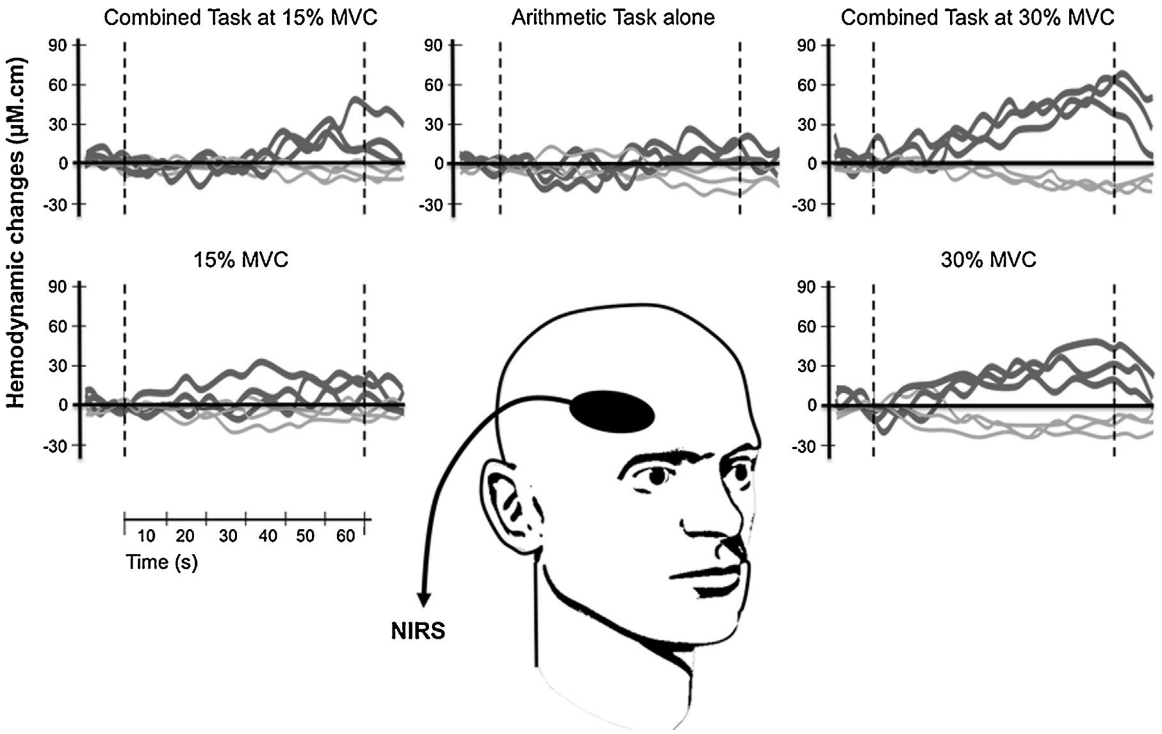

Fig. 3. Typical fNIRS hemodynamic changes. Cortical oxygenation changes are given in µM.cm for the subject 8 (3 trials performed per condition) in response to each different conditions of the protocol. The curves plotted either side of the horizontal line represent [HbO$_2$] (thick gray line) and [HHb] (thin gray line). Right prefrontal cortex was found activated at different levels of magnitude for arithmetic task alone, handgrip task at 15% and 30% MVC, and combined task for each level of grasping force. The vertical dotted lines indicate the start and end of the stimulus (60 s period).

in a specific brain region. Based on recent neuroimaging studies, it is suggested that the control of the attentional process during dual-tasks is associated with the activation of the (bi)lateral PFC (Atsumori et al., 2010; Holtzer et al., 2011; Stelzel et al., 2009; Tachibana et al., 2012). Hence, the task-related changes in oxygenation levels in the right PFC observed in our study may provide a limited window on how the PFC in concert with other brain regions and networks functionally acts during motor tasks with additional mental load. However, in the present study, we focused on a region of interest located over the right dorsolateral and frontopolar PFC using one channel NIRS setup. As mentioned in earlier neuroimaging studies, it is suggested that this particular brain region is underlying to participate in divided attention during dual-tasks (Atsumori et al., 2010; Holtzer et al., 2011; Stelzel et al., 2009; Tachibana et al., 2012). One methodological approach to show that attentional resources are required during a task consists of combining a first task to another task that requires attentional resources, while analyzing the human performance (i.e., various behavioral responses) of the second task. In the present study, we first observed higher force variability (assessed by SD) at 30% MVC as compared to 15% MVC, exhibiting more force fluctuations known to be signal-dependant (Missenard et al., 2008). Force fluctuations have been proposed to be due to the interaction of multiple features of motor-units population activity, including discharge rate variability, motor-units synchronization and low-frequency common oscillation (Taylor et al., 2003). In addition, performing an additional mental task during a handgrip task at 30% MVC further increased the variability of the grasping force ($p < .01$; $d = 0.47$). It may indicate that the subjects presented some difficulties in keeping the appropriate target force level due to a merely attentional resources divided. This extra rise of force variability was concomitant with (i) the perception of stress level (i.e., VAS scores), and (ii) the fall in mental performance (i.e., % of correct answers). First, the higher VAS scores occurred during the dual-task condition where the subject resources to meet demand were merely extended. Second, we found that the performance on the mental task decreased (from ∼3% at 15% MVC to 8% at 30% MVC compared to the control condition) whereas the force variability increased

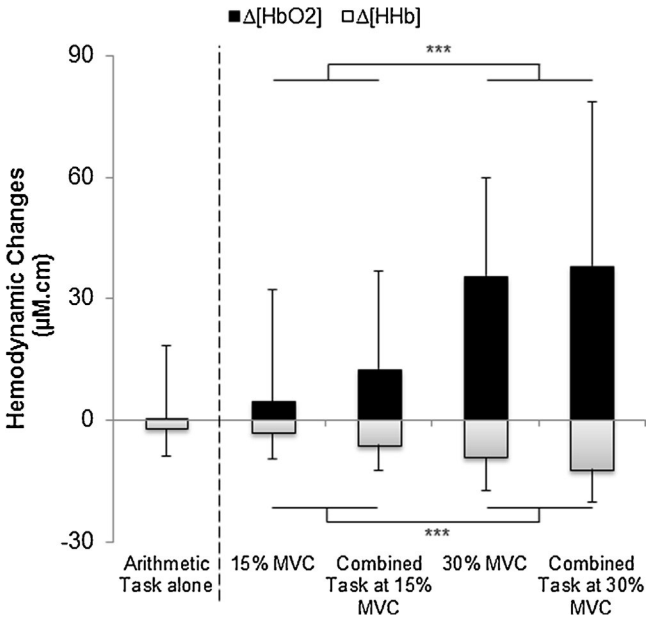

Fig. 4. Amplitude-based approach for fNIRS hemodynamic changes. Data results (mean ± SD) were given in relative concentration (Δ). [HbO$_2$] (in black) and [HHb] (in gray) concentrations are presented in response to the control condition and the handgrip tasks at two submaximal force levels (15% and 30% MVC) with (i.e., combined task) or without an additional arithmetic task. MVC, maximal voluntary contraction; ***$p < .001$.

(∼+82% between 15% and 30% MVC). Taken together, we are confident that our dual-task involved likely divided attention and that the level of force at 30% MVC required more attentional resources than at 15% MVC. As expected, participants reported higher RPE and perceived stress when force output alone increased, and a prominent increase in perceived stress (VAS scores) when performing the cognitively demanding task assessed with the DP15 scale as "somewhat difficult". Based on all of these subjective measurements and MVC values during pre- and post-testing session, we consider that our protocol successfully induced varied conditions of exertion and stress to the subjects by manipulating different experimental loading conditions without the influence of muscle fatigue.

We selected the PFC region because of (i) its properties underlying a role in cognitive control (Miller and Cohen, 2001), (ii) its role in motor planning and execution of movement, and (iii) its involvement in allocation and coordination of attentional resources (Atsumori et al., 2010). The mental arithmetic task (through a concurrent serial subtraction task) used in this study was previously shown to activate successfully the right and left PFC regions in a large sample of women but a small sample of men (as demonstrated in fNIRS studies reported by Sakatani et al., 2010; Tanida et al., 2004, 2007, 2008). In the present study, we found in 15 healthy men that (i) the right PFC activation increased significantly when increasing the submaximal levels of force; (ii) but combining such a task with a mental task did not increase significantly the activation of the right PFC area as compared to a single motor task.

First, the generation of static force resulted in a highly significant fNIRS response in the right PFC between the two submaximal force levels with greater [HbO_2] and [HHb] at 30% MVC compared to 15% MVC ($p < .001$; Fig. 4). This results is in agreement with previous studies that have revealed positive relationships between NIRS-measured motor cortical activation and isometric handgrip contractions ranging from 10% to 50% of MVC (Derosiere and Perrey, 2012; Shibuya et al., 2008). This indicates that the activity of the PFC and motor areas were relied on the amount of muscular force to produce even at low grip forces, and that moderate physical load could be evaluated reasonably by fNIRS.

Second, we observed a slight but no significant increase of fNIRS response (HbO_2 and HHb) during dual-task condition. We propose that the lack of further rise in PFC oxygenation levels for the additional mental task (Fig. 4) could be associated with the degradation of performance (increase of errors from ∼3 to 8% at 15 and 30% MVC, respectively). Indeed, it can be suggested that since the right PFC activation does not increase any more, no additional cerebral output is "produced" by this area driving to the incapacity to adequately perform the mental task (Stelzel et al., 2009).

In other words both behavioral and fNIRS responses suggest that participants were unable to invest more attention and effort in performing the more difficult levels in order to maintain mental performance at an acceptable level.

In the projected experimental conditions of our present study (submaximal motor and moderate mental loads for mimicking daily tasks), results may be explained also by a differing response sensitivity to stimulus for [HbO_2] as compared to that of [HHb]. While the [HbO_2] signal tends to increase regardless of the conditions (Fig. 4), a greater SD in [HbO_2] signal than in [HHb] was observed. Physiological noise, independent of the functional activation such as spontaneous oscillations (e.g., vasomotion, pulse and breath waves) have been shown to be more important in [HbO_2] when compared to [HHb], thereby increasing variability of the hemodynamic response (Obrig and Villringer, 2003). The simple reason to favor [HbO_2] may be that changes are larger than those of [HHb]. The question is whether the high trend for [HHb] decrease ($p = 0.051$) shows a better signal-to-noise ratio with respect to the functionally induced changes when compared with the [HbO_2] changes. In addition, as proposed by Obrig and Villringer (2003), [HHb] decrease could be the most valid parameter for depicting the typical cortical activation. Under simple motor stimulations, previous data showed that HHb is the major factor in determining the time course of the blood-oxygen-level dependent signal derived from functional MRI (Strangman et al., 2002).

Finally, although the present study revealed interesting results on cortical activation during dual-tasking at submaximal force levels for a short duration of sustained exertion (i.e., 60 s), some limitations for interpreting fNIRS responses need to be addressed. First, fNIRS-measured brain activation was recorded only with one optode over a limited part of the right prefrontal cortex instead of a more sophisticated multi-channel covering larger areas of both PFCs. Second, no systemic measurements such as muscle hemodynamic, blood pressure, or heart rate were recorded simultaneously in the design of the current study. However, during static exercise, a condition where sympathetic activity is elevated, Ogoh et al. (2010) showed that cerebral autoregulation remains intact. In the present study, by selecting low handgrip contractions (15 and 30% MVC) for a short duration of stimulation (60 s) we probably minimized any strong metaborecepetor and mechanoreceptor signals to the brain. In adition, handgrip and mental arithmetic stimuli do not interact in a synergistic or additive manner in generating cardiovascular and autonomic responses (Wasmund et al., 2002). On the whole, we can reasonably assume that cortical hemodynamic responses in the context of our study (60 s of handgrip task at 15 and 30% MVC with additional mental task) were unlikely influenced by any systemic influences. A third limitation is that we only studied one type of mental workload, whereas other types of mental and physical workload may differentially influence cerebral responses. Lastly, many complex factors likely contribute to how robustly [HbO_2] and [HHb] activation are coupled in NIRS experiments, including the equipment used, the areas of the brain examined, optode positioning and location, and population factors (see Gervain et al., 2011).

5. Conclusion

The results of this study provide evidence that PFC oxygenation responses increased as a function of submaximal motor task loading. Additionally, during the dual-task paradigm (i.e., while performing handgrip effort at 30% MVC in combination with mental load), the fNIRS-derived responses showed an increase in PFC activation. However, a significant over-activation effect of the PFC was not clearly evidenced. This investigation provides important initial information about the influence of physical and mental workload measured by fNIRS, albeit future research should explore the impact of different mental workload on physical tasks on human performance.

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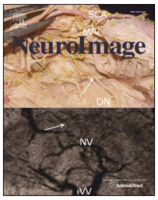

Expectations induced by natural-like temporal fluctuations are independent of attention decrement: Evidence from behavior and early visual evoked potentials

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ABSTRACT

Temporal expectations and attention decrement affect human behavior in opposing ways: the former positively, the latter negatively yet both exhibit similar neural signatures – i.e., reduction in the early event-related potential components' amplitude – despite different underlying mechanisms. Furthermore, there is a significant and growing debate in the literature regarding the putative role of attention in the encoding of expectations in perception. The question then arises as to what are the behavioral and neural consequences, if any, of attention decrement on temporal expectations and related enhancement of sensory information processing.

Here, we investigated behavioral performance and visual N1a, N1p and P1 components during a sustained attention reaction time task inducing attention decrement under two conditions. In one condition, the inter-stimulus intervals (ISIs) were randomly distributed to impede expectation effects while for the other, the ISI exhibited natural-like long-term correlations supposed to induce temporal expectations.

Behavioral results show that natural-like fluctuations in ISI indeed induced faster RT due to temporal expectations. These temporal expectations were beneficial even under attention decrement circumstances. Further, temporal expectations were associated with reduced N1a amplitude while attention decrement was associated with reduced N1p amplitude. Our findings provide evidence that the effects of temporal expectations and attention decrement induced in a single task can be independent at the behavioral level, and are supported at separate information processing stages at the neural level in vision.

Introduction

In contemporary daily living, human beings encounter rich information flows that must be effectively processed with finite and relatively limited cognitive resources. As a result of this mismatch, information is not processed in an equally efficient manner at each instant in time (VanRullen and Koch, 2003). For example, temporal expectations of events with high probability of occurrence constrain perception to particular moments in time (Nobre et al., 2007), thereby inducing behavioral enhancements (*e.g.*, improving response times to imperative signals). As a contrasting example, time can also adversely impact perception, as occurs during sustained attention tasks where a gradual attention decrement arises over time (Derosière et al., 2013). While these contrasting effects of time on perception – and their neural substrates – have been extensively investigated separately, to date it is still unclear as to what extent, if at all, these effects are related. An understanding of such relationships may help contribute towards the emergence of an integrated view on how human behavior is affected by the temporal properties of stimulation in everyday life.

According to the predictive coding framework, the human sensory nervous system inherently encodes expectations about the natural world (Friston, 2005) based on statistical regularities in the environment (Ramnani, 2006). Coull and Nobre (2008) claim that temporal expectations can be induced by any temporal structure in the rate of stimulus presentation which allows some prediction of when the next stimulus will appear. Previous studies on temporal expectations have for instance exploited probabilistic (Miniussi et al., 1999) or rhythmic (Lange, 2009) cueing paradigms, in which cue stimuli provide relevant information about the timing of the upcoming target stimuli. When target stimuli appear at expected instants, the computational burden of perception is reduced (Summerfield and Egner, 2009), reaction times (RTs) are lower and responses more accurate than when stimuli are

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unexpected. However, such behavioral benefits of temporal expectations have yet to be appraised in response to naturally variable stimuli. In fact, the specific temporal structure of variability known as 1/*f scaling* or fractal *long-range correlation* (LC) is widely acknowledged as the ubiquitous outcome of natural (ecological, biological) systems (Markowitz et al., 2013; West and Shlesinger, 1989). Studies on perception of naturally variable visual scenes have shown that temporal correlations in pixel values (Rao and Ballard, 1999) and spatial correlations between neighboring pixels' intensities in a given image (Hosoya et al., 2005) allow the visual system to predict pixel variations over time and space. A series of events containing natural-like LC might then allow for efficient encoding of temporal expectations, thereby inducing behavioral benefits. In this event, one may wonder what the neural substrates underlying such behavioral enhancements in response to naturally variable stimuli would be. Although studies specifically targeting this question are lacking, electroencephalography (EEG) studies on temporal expectations using the aforementioned cueing paradigms demonstrated a reduction of the early, sensory components of the event-related potential (ERP) in response to target stimuli occurring at expected times (*e.g.*, reduction of the visual N1p, Doherty et al., 2005 and auditory N1, Lange, 2009). These findings can be interpreted in the light of predictive coding models which assume that (*i*) each stage of the sensory cortical hierarchy harbors "*representational neurons*" that could, it is speculated, encode expectations and "*error neurons*" that could encode (again, speculatively) the mismatch between expectations and the actual sensory input; and (*ii*) the lower this mismatch, the smaller the evoked response of the "*error neurons*" (Friston, 2005). In summary, temporal expectations are associated with better behavioral performance with a lower computational cost.

Focused attention represents another distinct and important mechanism facilitating perception and goal-directed behaviors (Busch and VanRullen, 2010). The act of focusing attention towards a specific object, feature or location involves a fronto-parietal network (Corbetta and Shulman, 2002) which pre-attentively modulates the activity of sensory brain areas (Kastner and Ungerleider, 2000). When the target event occurs, its detection is facilitated and the evoked neural response of sensory areas is increased (Kanwisher and Wojciulik, 2000), as measured by visual P1 and N1p enhancements (Hillyard et al., 1998). Nonetheless, such a top-down control of focused attention cannot be maintained indefinitely and undergoes the so-called time-on-task (TOT) effect, typically characterized by an increase in RT (Derosière et al., 2013). Marked changes in the neural activity of the attention-related fronto-parietal network accompany the TOT effect (Derosière et al., 2013). As a consequence, the attention-related modulation of the sensory brain areas' activity is altered (Weissman et al., 2006) and amplitudes of some of the early ERP components have been found to decrease in response to the TOT-induced attention decrement (Faber et al., 2012). Thus, sustaining attention involves a certain computational burden leading in turn to a reduction in sensory neural responses and a decrement in behavioral performance over time.

To put it succinctly, temporal expectations and TOT affect behavioral performance in opposing ways: the former positively, the latter negatively. Furthermore, these two effects may be regarded as bearing similar neural signatures (i.e., reduction in the amplitudes of the early ERP components) despite their distinct neural underpinnings. Given this, the interesting question arises as to what both the behavioral and neural consequences of attention decrement on the enhancement of sensory information processing induced by temporal expectations would be. This question is relevant in light of the ongoing scientific debate regarding the potential role of attention in the encoding of expectations in perception (Kok et al., 2012; Friston, 2009).

As a contribution towards providing an integrated view on the combined effects of temporal expectations and TOT on perception, the present study investigated behavioral and visual ERP activities during an 18-min visual sustained attention task performed under two conditions. In the first condition the inter-stimuli intervals (ISIs) were random so as to reduce temporal expectations. In the second condition, the ISIs were given a fractal LC. We formulated the following working hypotheses. First, a natural-like variable, i.e. long-range correlated ISI should induce lower RT compared to random ISI. Second, according to predictive coding models, the construction of expectations does not involve attention, even though so far this assumption lacks empirical evidence from studies manipulating attention and expectations orthogonally (Summerfield and Egner, 2009). Thus, based on predictive coding models, we hypothesized that temporal expectations are independent of attention capacities and would remain behaviorally beneficial even under attention decrement circumstances. Finally, at the neural level, we sought to test whether early ERP components provide specific signatures for the effects of temporal expectations on the one hand, and TOT on the other, or whether they are additively or multiplicatively affected by the two effects.

Materials and methods

Participants

Nineteen healthy male volunteers took part in the study (aged 26.6 ± 4.5 years, height 178.4 ± 6.6 m; body weight 70.9 ± 8.3 kg). All subjects were right-handed according to the Edinburgh Questionnaire (Oldfield, 1971) and had normal or corrected-to-normal vision. To control for any potential confounds, baseline levels of sleepiness were reported by the subjects using the Epworth Sleepiness Scale (ESS; Johns, 1991). Subjects having a score value higher than 9 on the ESS were not included in the study. Subjects' habitual caffeine intake had to be less than 5 cups per day and subjects had to be careful of the number of cups taken in the day before both experimental sessions. No subject declared any neurological, respiratory, and cardiovascular disease or medication, which might affect brain/cognitive functions. Each subject provided written informed consent prior to participation in the study. All procedures were approved by the local ethics committee (CPP Sud-Méditerranée II, number 2010-11-05) and complied with the Declaration of Helsinki for human experimentations.

Experimental design

Experiments were conducted in a quiet and dimly-lit room. The subjects were seated at a table in front of a 22-inch LCD monitor positioned at a distance of 1 m from the subject's eyes which was used to display the target stimuli during the sustained attention RT task. The left and right forearms were rested upon the surface of the table with the palms facing the table. A response switch box (BioSemi, Amsterdam, The Netherlands) was positioned under the dominant (i.e., right) hand with the response button under the index finger (see Fig. 1.A).

Experimental protocol

Participants came twice to the laboratory to perform the sustained attention task under two different conditions. The two experimental sessions were assigned in random order and separated by at least one week to reduce any potential learning effect. They were conducted at the same time of the day for each subject to avoid any chronobiological confounding effect on sustained attention abilities. Participants were not told that two different experimental sessions would be run and the instructions were identical for both sessions.

For both experimental sessions, the course of the protocol was identical. First, a simple visual RT task of 1 min duration was performed in order to familiarize the subjects with the paradigm. The visual target stimulus consisted of a white cross (size: 13 × 13 cm) displayed for 10 ms at the center of a black screen. Subjects were required to push the response button by flexion of the index finger as fast as possible in response to the visual stimulus. The mean of the generated ISI was set at 2000 ms, with a coefficient of variation of 30%. Once the

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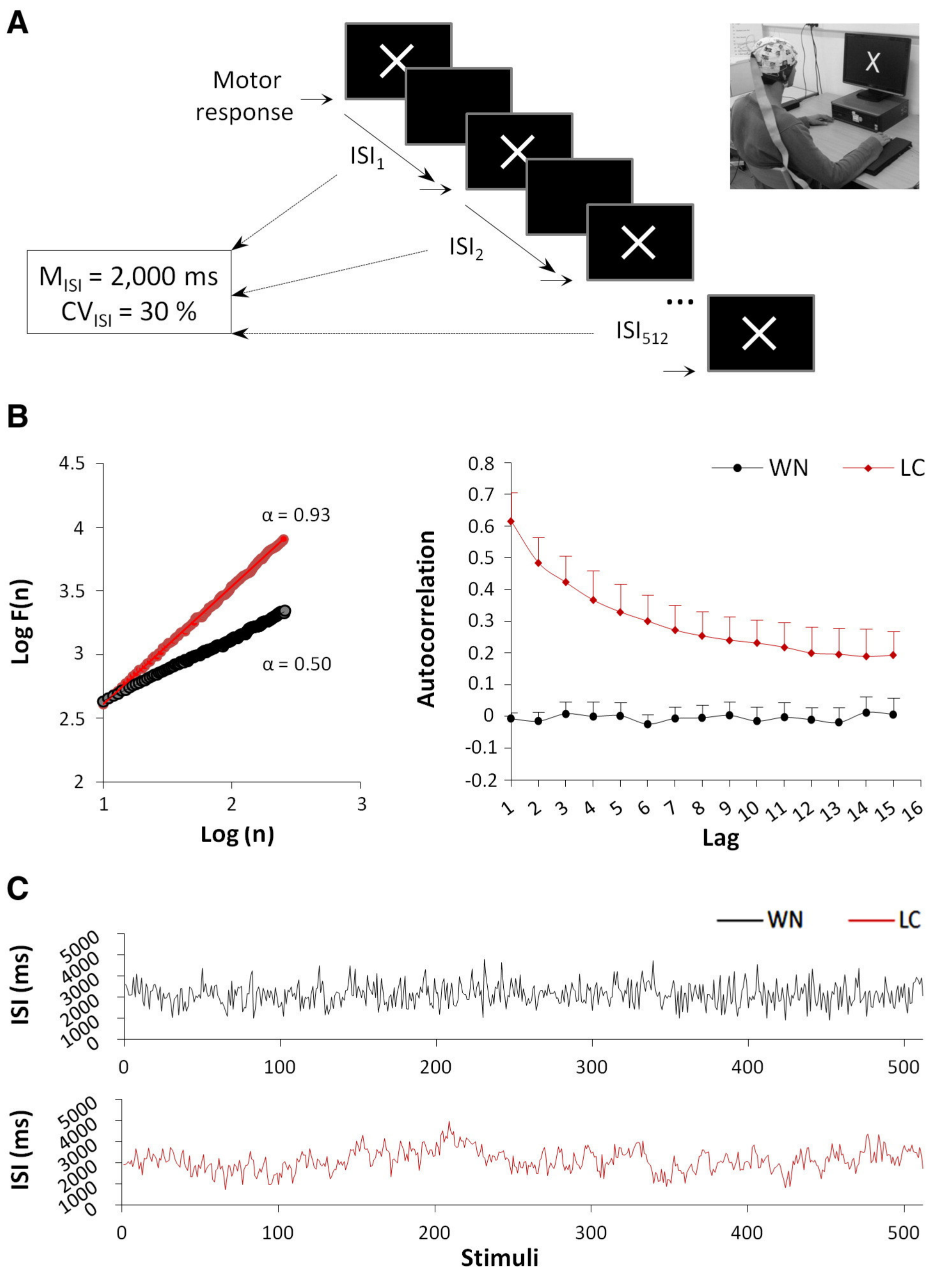

Fig. 1. Detailed experimental procedure during the sustained attention task. A. Experimental task and design. *Left*: illustration of the experimental paradigm. M_{ISI}: mean ISI over the task; CV_{ISI}: coefficient of variation. *Top-right*: picture of the experimental set-up. B. Structures of the measured ISI series. The averaged values represented in these figures result from the ISI series once the experiment was realized for the nineteen participants. *Left*: Results of DFA are represented in an averaged diffusion plot in bi-logarithmic coordinates. $F(n) \propto n^{\alpha}$ thus yields a linear diffusion plot, with α representing the regression slope. *Right*: average autocorrelation functions from lag 1 to lag 15 for LC (red) and WN (black) conditions. Vertical bars represent SD. C. Examples of measured ISI series for one single subject. ISI durations (y axis) as a function of ISI indices over task time (x axis) in the WN (top graph) and LC (bottom graph) conditions. Visual inspection shows locally persistent trends in ISI, characteristic of long-range correlated fluctuations as compared to white noise.

familiarization phase was realized, subjects were instructed to rest for 4 min (2 min eyes open followed by 2 min eyes closed) in order to stabilize the EEG signals. At the end of the resting phase, subjects performed the sustained attention task. Characteristics of the visual stimuli and ISI were the same as described above but the entire task comprised 513 stimuli. A series of 513 stimuli (i.e., 2^9 ISI) were exploited as such a length has been shown to allow for reliable generation and characterization of LC properties (*e.g.*, Delignieres et al., 2006). Once the entire experiment was completed, we verified that the experimental ISI series actually presented the properties of the input series. The measured ISIs were 2140 ± 20.5 ms (mean ± SD), so that the sustained attention task duration was 18 min and 30 s on average (i.e., 513 × 2140 ms). The experimental protocol is presented in Fig. 1.A.

The two experimental conditions differed only in the structure of fluctuations of the ISI presented during the sustained attention task. To characterize the structure of ISI fluctuations, we used autocorrelation analysis and standard Detrended Fluctuation Analysis (DFA; Peng et al., 1993), a well-established and robust method for monofractal analysis (Delignieres et al., 2006). Basically, DFA exploits the diffusion properties of the time series, assessing the relationship between the mean amplitude of fluctuations ($F(n)$) and the size (n) of the window within which the fluctuations are observed. LC series typically yield a power

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relationship obeying $F(n) \propto n^{\alpha}$, characterized by a scaling exponent α close to 1 ($\alpha \in [0.75, 1.25]$) while for white noise (WN), α is close to 0.5.

In the LC condition, ISI series were generated so as to satisfy $\alpha = 0.95$ (±0.06), and the autocorrelation function showed the typical asymptotic power-law decay over increasing lags (see Fig. 1.B), meaning that statistical memory between ISI persisted even for a large number of intervening ISI (Beran, 1994). ISI series in this condition were then $1/f$ noise, meaning they exhibited persistent LC. In the WN condition, ISI series were random and satisfied $\alpha = 0.50$ (±0.03), the serial autocorrelation being zero for all lags (Fig. 1.B). For each condition, a pool of 19 ISI series (i.e., one per participant) with similar statistical properties was generated on Matlab® (The MathWorks, Inc., Natick, MA, USA) before the experiment using the algorithm developed by Davies and Harte (1987). Stimulus presentation was then controlled using the Presentation software package® (version 16.2, www.neurobs.com) on a standard Microsoft Windows computer system. To confirm that the experimental ISI series actually presented the statistical properties of the input series, DFA and autocorrelation analysis were applied to the measured ISI series for both conditions. These analyses confirmed that our experimental device succeeded in generating the desired fluctuation structure for the input ISI: $\alpha = 0.93$ (±0.06) and $\alpha = 0.50$ (±0.04) for LC and WN conditions, respectively. Characteristics of the measured ISI series are presented in Figs. 1.B and C.

Data collection

EEG was recorded continuously and amplified using a BioSemi Active-two system (BioSemi B.V., Amsterdam, The Netherlands) with 32 Ag/AgCl active electrodes relative to a scalp reference. EEG was recorded continuously from DC to 2048 Hz. BioSemi systems work with a "zero-ref" setup with ground and reference electrodes replaced by a Common Mode Sense/Driven Right Leg circuit (CMS/DRL; for further information, please refer to http://www.biosemi.com/faq/cmsdrl.htm). The 32 EEG electrodes were placed according to the International 10–20 System (Jasper, 1958) by means of an electrode cap. CMS and DRL electrodes were placed at the scalp level between C3 and Cz, and Cz and C4, respectively. Motor responses were recorded using the response switch box. Stimuli and motor triggers were recorded through the A/D box of the BioSemi system.

Data analysis

Behavioral data

All data were processed through Matlab and using the Fieldtrip toolbox (Nijmegen, Amsterdam; Oostenveld et al., 2011). The RT was measured as the time between the onset of the visual stimulus (target stimulus) and the onset of the motor response. Responses were considered valid if the response button was pressed more than 150 ms following stimulus onset. A similar cut-off time point has been applied in previous RT studies (*e.g.*, Derosière et al., 2014; Faber et al., 2012) and facilitates the exclusion of anticipatory motor responses (i.e., occurring between 0 and 150 ms post-stimulus) from our analyses. On this basis, we calculated for both conditions the average RTs obtained for three non-overlapping blocks of 6 min duration: 0 to 6 min, 6 to 12 min, and 12 to 18 min of the task. For each block, misses and false alarms (FA) were counted as well. Misses were defined as stimuli which were not followed by any motor response and FA were defined as motor responses having occurred while no visual stimulus occurred.

EEG data

The continuous EEG recordings were downsampled to 512 Hz and off-line segmented in 1400 ms epochs starting 400 ms before and finishing 1000 ms after stimulus onset. To ensure good quality ERPs, several inclusion criteria were applied to the trial selection such that trials comprising (*i*) a motor response during the pre-stimulus period (i.e., during −400 and 0 ms), (*ii*) more than one motor response between stimulus onset and +600 ms or (*iii*) a motor response between stimulus onset and +150 ms, were excluded. On the defined epoch of interest, we applied an automatic artifact rejection algorithm which identified and rejected large jump and muscle artifacts (i.e., originating from electromyography sources) by means of thresholding the z-transformed values of band-pass filtered and raw data. Cutoff z-values were determined based on visual inspection of five subjects' recordings, and set at 25 and 15 for jump and muscle artifacts, respectively, and using band-pass (110 to 140 Hz) filtered data for detecting muscle artifacts. These automatic steps, coupled with visual inspection of remaining trials, were carried over to clear the data from trials with large artifacts. The remaining trials were high-pass filtered using a cutoff frequency of 0.5 Hz, in order to remove slow drifts. Subsequently, the Independent Component Analysis (ICA) technique was applied in order to remove common artifacts from the recordings (Delorme et al., 2007). Careful joint inspection of the power spectrums, scalp topographies and ERPs of components facilitated the evaluation of specific components for artifact rejection. Once undesirable components were identified, the EEG signals were back-projected based on the other independent components. The remaining data were screened manually for residual artifacts and we subsequently applied baseline correction on the artifact-free trials. The baseline interval for correcting ERPs extended from −400 ms to 0 with respect to target stimulus onset. Average ERPs were computed for each of the two conditions for every 6-min block (i.e., 0 to 6 min, 6 to 12 min and 12 to 18 min of the task). We computed ERPs by pooling the values of neighboring electrodes within regions of interest (ROIs). According to the literature (Hillyard et al., 1998; Di Russo et al., 2003, 2005, 2008, 2013), there are three early, sensory components which can be distinguished in the visual evoked potential that are present within two separable ROIs: the P1, and the posterior and anterior N1 (i.e., N1p and N1a). For each of these early, sensory components, ROIs were identified on the basis of known results from the scientific literature (*e.g.*, Smit et al., 2007) and also based on the measured scalp topographies. The P1 and N1p components were analyzed in a posterior ROI including parieto-occipital electrodes (O1, O2, PO3, PO4, P7, P8, Oz) while the N1a was analyzed in an anterior ROI including frontal electrodes (Fp1, Fp2, AF3, AF4, F3, F4, Fz). Finally, a peak detection algorithm was applied to the individual ERPs in order to extract peak amplitude and latency values for the components of interest. The time ranges used for identification of P1, N1a and N1p peaks were determined from a visual inspection of subjects' ERPs and through known results in the literature (*e.g.*, Muñoz-Ruata et al., 2010; Smit et al., 2007) and were of 70–120 ms, 80–170 ms and 120–190 ms post-stimulus, respectively. All detected peaks were verified by visual inspection to confirm that each computed individual value was well-supported from the individual graphs. These confirmed P1, N1a and N1p peak amplitudes and latencies were recorded for subsequent statistical analysis.

Statistical analysis

Statistica software (version 7.0, Statsoft, Oklahoma, USA) was used for all analyses. All data were examined for normality and homogeneity of variance using Skewness, Kurtosis, and Brown–Forsythe tests. P1, N1a and N1p peak amplitudes and latencies as well as RT data presented normal distributions and homogeneity of variance. Therefore, two-way repeated-measure ANOVAs were used to test for any significant effects of (*i*) time-on-task (0–6 min, 6–12 min and 12–18 min) and (*ii*) experimental condition (WN and LC) on RT and on P1, N1a and N1p peak amplitudes and latencies. All these data were systematically tested for the sphericity assumption using Mauchley's tests. The Greenhouse–Geisser correction was used for sphericity when necessary. When appropriate, the Fisher's LSD post-hoc test was used to detect paired differences. Because of the non-normal distribution of the misses and FA samples, nonparametric Friedman ANOVAs were performed to test for the significant effects of TOT and condition on these

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data. The significance level was set at $p < 0.05$. Data are presented mean ± standard deviation (SD), unless specified.

Results

Behavioral results

A significant increase in RT was observed as a function of TOT (Greenhouse–Geisser corrected: $F_{1,26} = 21.4$; $p < .001$). Also, RT was significantly higher in the WN condition compared to the LC condition ($F_{1,18} = 18.4$; $p < .001$). These results are presented in Fig. 2. No significant interaction effect (TOT × condition) was found on RT data ($F_{2,36} = 0.1$; $p = .98$). No significant effect of TOT or condition was found on FA data ($Fr_{5,19} = 6.5$; $p = .26$) and misses ($Fr_{5,19} = 9.6$; $p = .09$), although a trend was apparent in terms of an increase in the number of misses over TOT for both conditions.

EEG results

P1 amplitude and latency

The P1 component occurred at 98 ± 11 ms post-stimulus on average. P1 amplitude did not significantly change, neither as a function of TOT (Greenhouse–Geisser corrected: $F_{2,28} = 3.1$; $p = .07$), nor as a function of condition ($F_{1,17} = 0.5$; $p = .49$), and no significant interaction effect (TOT × condition) was found on P1 amplitudes ($F_{2,34} = 0.18$; $p = .84$). P1 latency did not significantly change, neither as a function of TOT ($F_{2,34} = 0.15$; $p = .86$), nor as a function of condition ($F_{1,17} = 0.1$; $p = .97$), and no significant interaction effect (TOT × condition) was found on P1 latencies ($F_{2,34} = 1.32$; $p = .28$). Grand-averaged P1 waveforms and scalp topographies are presented in Fig. 3 for each experimental condition.

N1a amplitude and latency

The N1a component occurred at 118 ± 18 ms post-stimulus on average. N1a amplitude did not significantly change as a function of TOT ($F_{2,36} = 2.3$; $p = .11$) but was significantly lower in the LC condition than in the WN condition ($F_{1,18} = 5.3$; $p < .05$). No significant interaction effect (TOT × condition) was found on N1a amplitudes ($F_{2,36} = 0.3$; $p = .78$). These results are presented in Fig. 4. N1a latency did not significantly change, neither as a function of TOT ($F_{2,36} = 2.2$; $p = .13$), nor as a function of condition ($F_{1,18} = 0.5$; $p = .47$), and no significant interaction effect (TOT × condition) was found on N1a latencies ($F_{2,36} = 0.6$; $p = .56$).

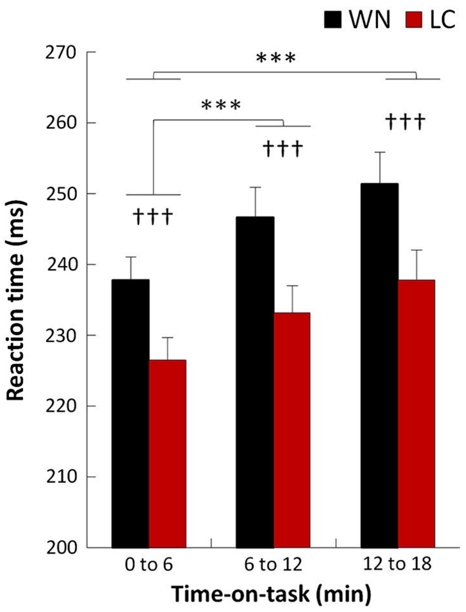

Fig. 2. Evolution of reaction time over time during a sustained attention task $^{***}p < .001$ for differences between 6-min blocks; $†††p < .001$ for differences between conditions. Vertical bars represent SE.

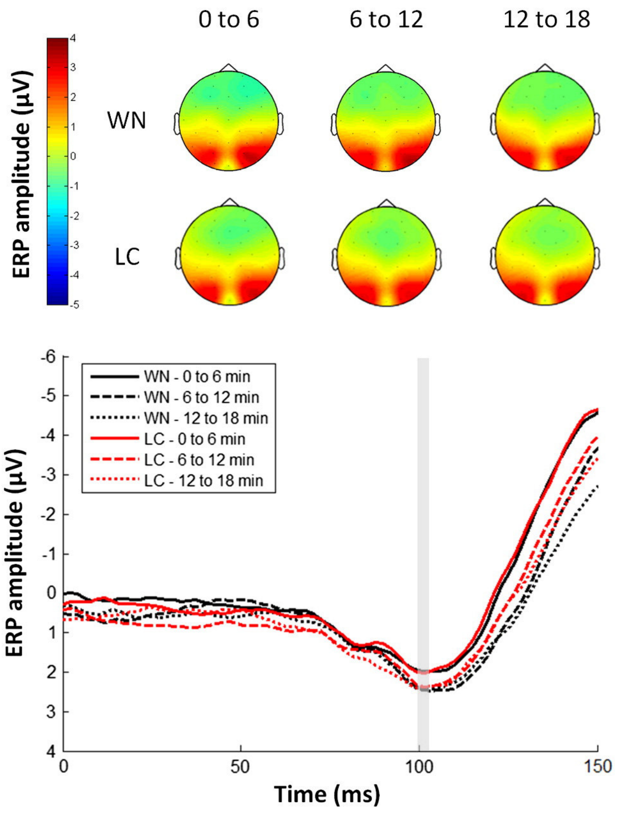

Fig. 3. Grand-averaged P1 results. *Top*: Scalp topographies of the grand-averaged P1 for each condition and each 6-min duration block. These topographies clearly show that there was no effect of temporal expectation and of TOT over the parieto-occipital electrodes. *Bottom*: Grand-averaged P1 waveforms. Time courses show data averaged across electrodes in the parieto-occipital region of interest (i.e., as defined in the EEG data section).

N1p amplitude and latency

The N1p component occurred at 157 ± 12 ms post-stimulus on average. N1p amplitude significantly increased as a function of TOT (Greenhouse–Geisser corrected: $F_{1,26} = 5.5$; $p < .05$) but did not significantly differ between conditions ($F_{1,18} = 0.5$; $p = .50$). No significant interaction effect (TOT × condition) was found on N1p amplitudes ($F_{2,36} = 0.3$; $p = .73$). Similarly, N1p latency significantly increased as a function of TOT ($F_{2,36} = 17.5$; $p < .001$) but did not significantly differ between conditions ($F_{1,18} = 0.1$; $p = . 89$). No significant interaction effect (TOT × condition) was found on N1p latencies (Greenhouse–Geisser corrected: $F_{1,24} = 0.2$; $p = .73$). These results are presented in Fig. 5.

Discussion

The aim of the study described here was to highlight the concomitant effects of expectations induced by natural-like temporal fluctuations and TOT on visual perception and related behavioral performance. As hypothesized, fractal fluctuations over time induced temporal expectations, as evident from the finding of a significantly faster RT in the LC condition compared to the WN condition. Also, our experimental design induced a TOT effect in both conditions as revealed by the significant increases in RT over time. Despite the TOT effect, temporal expectations remained beneficial for behavioral performance throughout the sustained attention task, as the RT remained shorter in the LC than in the WN condition throughout the TOT period. Interestingly, analyses at

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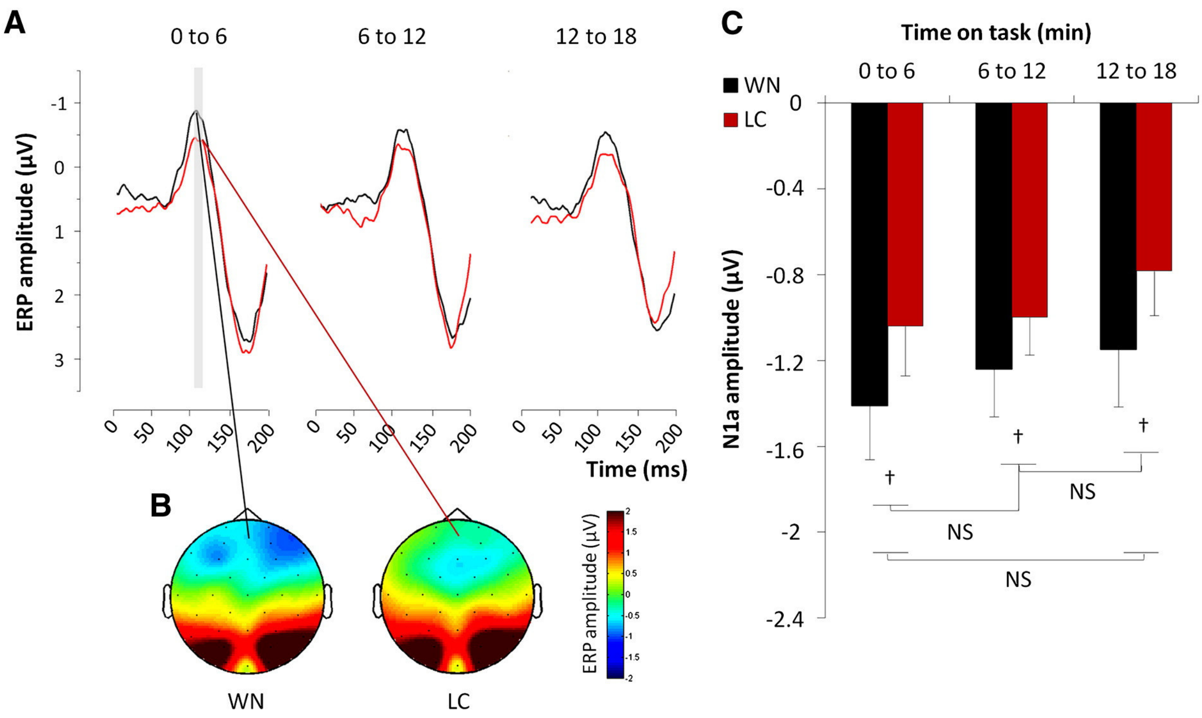

Fig. 4. Grand-averaged N1a and statistical results. A. Grand-averages (n = 19) from the frontal ROI for each condition as a function of TOT. Black lines: WN condition. Red lines: LC condition. Time courses show data averaged across electrodes in the frontal region of interest (i.e., as defined in the EEG data section). B. Scalp topographies of the grand-averaged N1a component for the 0 to 6 min block. The topographies clearly show the difference in N1a amplitude over the frontal electrodes as a function of condition. Note that posterior positivity is related to the late deflection of the P1 component, which occurs in the same time range as the N1a (the P1 time window can be observed in Figs. 3 and 5.A; for similar results, please refer to Vogel and Luck, 2010). C. Statistical results on N1a amplitude data. NS: non-significant; †$p < .05$. Vertical bars represent SE.

the neural level demonstrate that these two different effects on behavioral performance manifest as distinct early components of the visual evoked potential. Temporal expectations significantly decreased N1a amplitude but did not significantly impact N1p features (i.e., amplitude and latency) while the TOT effect significantly decreased N1p amplitude and increased its latency but did not significantly impact N1a features.

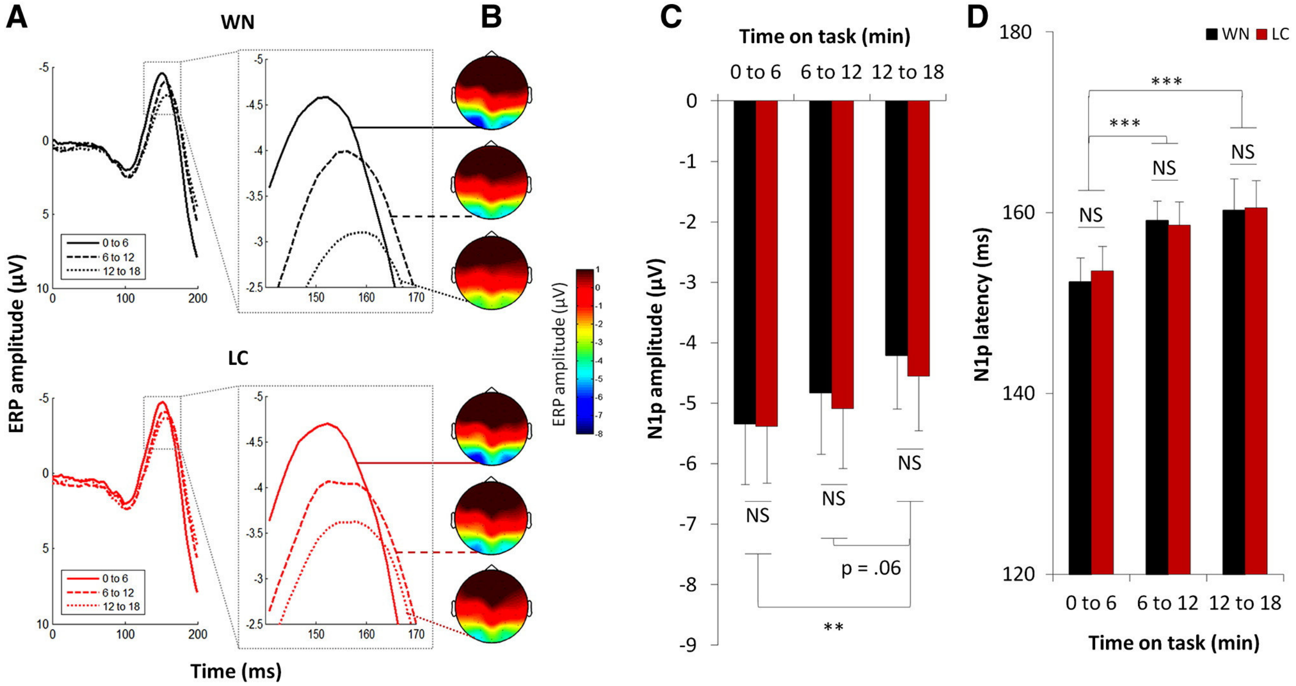

Fig. 5. Grand-averaged N1p and statistical results. A. Grand-averages (n = 19) from the parieto-occipital ROI for each block of the task and both conditions. Time courses show data averaged across electrodes in the parieto-occipital region of interest (i.e., as defined in the EEG data section) including an expanded view of the relevant N1p time range which shows the increase in N1p latency and the decrease in N1p amplitude as a function of TOT for each condition. B. Scalp topographies of the grand-averaged N1p component for each 6-min duration block of the task. For each condition, from top to bottom are represented the topographies for the 3 blocks of the task. The topographies clearly show the difference in N1p amplitude over the parieto-occipital electrodes as a function of TOT. C. Statistical results on N1p amplitude data. NS: non-significant; **$p < .01$. D. Statistical results on N1p latency data. NS: non-significant; ***$p < .001$. Vertical bars represent SE.

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Before focusing on a discussion of these different time-related neural activity changes, we first discuss a number of relevant behavioral considerations.

Behavioral consequences of (LC-induced) temporal expectations and TOT

To the best of our knowledge, the present study is the very first to explore the effect of temporal expectations on behavioral performance in the case of interactions with a natural-like fluctuating temporal series of events. By exploiting fractal LC series of stimuli, we were able to reproduce behavioral benefits habitually observed in probabilistic and rhythmic cueing paradigms (i.e., speeding of responses to imperative signals). This noteworthy finding is in line with aforementioned studies on perception of natural scenes demonstrating the ability of the human perceptual system to exploit temporal and spatial correlations between pixel values to predict future pixel variations (Rao and Ballard, 1999). The ability of humans to exploit correlations present in the natural environment might result from evolution and/or development, and is potentially the basis of efficient coding of natural sensory information (Hosoya et al., 2005). In particular, according to the *Complexity Matching* principle initially developed in the field of physics, the efficiency of information transmission would be maximal when two systems exhibit similarly complex 1/*f* – or long-range correlated – dynamics (West et al., 2008, West and Grigolini, 2010a). Consequently it is plausible that human perceptual processes are, through a process of evolutionary adaptation, optimally efficient when responding to stimuli exhibiting such naturally occurring long range structural scaling. A corollary of the complexity matching effect has been shown to be the contingency of the psychophysical phenomenon of habituation, meaning a decrease/suppression of neural/behavioral responsiveness to a repeated stimulus over time. Indeed, while habituation occurs when confronted with a simple stimulus (*e.g.*, periodic, uncorrelated, *etc.*), responsiveness to complex stimuli persists (West and Grigolini, 2010a, 2010b). Taking a broader view, the connection with the TOT effect here seems obvious, and, when one considers potential applications in the context of human–artificial environment interaction, deserves further investigation as to the relevant neuro-behavioral underpinnings.

Our experimental design allowed us to investigate attention and expectation orthogonally and to examine the resulting effects on behavioral performance. By inducing both attention decrement and temporal expectations during a single task, we were able to assess the influence of attention capacity on the encoding of temporal expectations. The issue is of significant importance given ongoing debates regarding the putative role of attention within predictive coding schemes (Kok et al., 2012; Friston, 2009; Summerfield and Egner, 2009). We hypothesized that the effect of temporal expectations on behavioral performance would be independent of attention capacity. Interestingly, our RT results demonstrate that the behavioral benefits associated with LC-induced temporal expectations are still present under attention decrement conditions, the RT remaining consistently shorter in the LC than in the WN condition while the TOT effect occurred. Thus, our results provide empirical evidence supporting the idea that the encoding of temporal expectations does not depend on changes in attentional capacity as induced by TOT. Analyses at the neural level provide further evidence of the distinguishability of the two time-related effects, as described next.

P1 features unchanged with temporal expectations and TOT effect

According to Di Russo et al. (2008), the P1 could represent the first processing stage of visual information following a stimulus presentation (occurring at 98 ± 11 ms post-stimulus in the present study), and may reflect the conjoined engagement of two secondary visual cortical areas, namely the dorsal V3 and the ventral V4 (Di Russo et al., 2001, 2003; Mangun et al., 1997; Martinez et al., 1999). Our experimental design produced no effect on P1 features either by TOT, or by temporal expectations.

As mentioned in the introductory section, P1 enhancement is a well-known signature of focused attention, and has contributed to the development of the assumption that attention acts as a "*sensory gain mechanism*" (Hillyard et al., 1998). ERP results in this study and in previous studies (Boksem et al., 2005; Faber et al., 2012) demonstrate that P1 features are robust to the TOT effect. Yet, Weissman et al. (2006) found a decrease in the event-related hemodynamic response of the secondary visual areas with TOT effect, involving an alteration of the dorsal V3 and the ventral V4 activities. Taken together, these results suggest that the activity of visual secondary areas can be altered by attention decrement but such alterations may have occurred at a later processing stage in the present study.

The early processing stage of visual information was also insensitive to temporal expectations as elicited by our experimental design. Exploiting other experimental designs thought to induce temporal expectations (i.e., using cueing paradigms), some authors have brought to light an enhancement of the P1 amplitude, both in vision (*e.g.*, Correa et al., 2006) and in audition (*e.g.*, Lange et al., 2006). A recent literature review and conceptual analysis (Lange, 2013) has led to the suggestion that, in these studies, task characteristics were favorable to inducing the orienting of attention in time, leading in turn to a confounding effect on the changes in early ERP components' amplitude. In this case, attention acts as a sensory gain mechanism and the expected reduction in P1 amplitude due to temporal expectations is potentially "hidden" by the positive effect of attention (Lange, 2013). It is however worth noting that, when task characteristics allow the encoding of temporal expectation without the temporal orienting of attention, the early ERP components' amplitude is presumed to be diminished (Lange, 2013). Yet, it was not the case in the present study. This finding can be interpreted in the light of multi-level hierarchical predictive coding models which postulate that, at the earliest processing stage, predictions are based on local transition probabilities, as induced by stimulus repetition (Todorovic and de Lange, 2012; Wacongne et al., 2011). In our experimental design, such low-level expectations could have been elicited if certain consecutive ISIs had been of exactly the same duration, as in an isochronous metronome. However, given that (*i*) each ISI was different from its directly preceding neighbor in both conditions, and that (*ii*) ISI series in both conditions presented the same level of variability (CV 30%), error neurons (i.e., neurons encoding the mismatch between expectations and the actual sensory input) at this early processing stage may have discharged in a similar pattern in both conditions, which could explain the absence of effect of the experimental condition on P1 features. In the framework of hierarchical predictive coding models, more complex statistical regularities in the environment, as induced in the present LC condition, would involve higher-order expectations that are potentially processed at the subsequent neural level, in a sequential mode (Todorovic and de Lange, 2012; Wacongne et al., 2011). In the present study, this subsequent neural level is represented by the N1a component.

N1a reduction with temporal expectations

The second component occurring post-stimulus was the N1a (at 118 ± 18 ms post-stimulus in the present study). N1a is thought to occur following the depolarization of forward connections (Di Russo et al., 2008) projecting from secondary visual areas (i.e., where the P1 is evoked) to the intraparietal sulcus where its neural generators have been located (Di Russo et al., 2003, 2005). We found a suppression effect of temporal expectation over the N1a component.

Previous studies on temporal expectations in vision did not report N1a results, and focused on N1p and other components of the visual evoked potential (Miniussi et al., 1999; Doherty et al., 2005). The omission of N1a observations is potentially linked to the history of the study of the N1a component, which was for the first time distinguished from N1p through spatial attention paradigms (see Hillyard et al., 1998), and then mainly studied in this context (*e.g.*, Di Russo et al.,

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2001, 2003, 2008; Makeig et al., 1999). Yet, the reduction of the N1a amplitude reported here is of substantial interest for our understanding of how temporal expectations are encoded, and this finding further reinforces the hierarchical view of predictive coding models. Indeed, the results reported here support the interpretation that higher-order temporal expectations involve an intermediate processing stage (i.e., occurring after the P1-related cortical activity), and suggest that this processing stage would potentially take place in the intraparietal cortex. Wacongne et al. (2011) pointed out an engagement of parietal areas at a late processing stage in response to high-order expectations of *what* would be the forthcoming stimuli. Our findings, complementarily, suggest that the intraparietal cortex may be involved in response to high-order expectations of *when* the forthcoming stimuli should occur. This interpretation is in line with a compendium of findings that have demonstrated the sensitivity of the intraparietal cortex to predictable foreperiods (Sakai et al., 2000), temporally informative cues (Coull and Nobre, 1998), hazard functions (Janssen and Shadlen, 2005) or, more generally, to implicit timing (Coull and Nobre, 2008). To go a step further along this line of inquiry, future studies should examine the potential relationship between (*i*) the temporal expectation-related changes in RT and (*ii*) the single-trial variations in N1a amplitude — an issue that has not been addressed in the study presented here.

Furthermore, the N1a component remained unaffected by the TOT effect, demonstrating that the processing stage represented by this component was sensitive to temporal expectations exclusively. That is, our results suggest that changes in the fronto-parietal network activity habitually associated with TOT effect (Derosière et al., 2013) did not involve changes in the evoked response of the intraparietal cortex. In contrast, the visual evoked potential was altered by TOT at a later processing stage, reflected by the N1p.

N1p affected by TOT effect

The N1p was the third and last component investigated (occurring at 157 ± 12 ms post-stimulus in the present study). This component has been interpreted as occurring following the depolarization of backward connections (Di Russo et al., 2003, 2008) projecting from parietal areas (i.e., where the N1a is evoked) to the V3 areas which house its neural generators (Di Russo et al., 2001, 2003; Mangun et al., 1997; Martinez et al., 1999). This reactivation of visual cortices is considered to result from a top-down modulation of visual cortices activity arising from the fronto-parietal network and allowing for a deepening of information analysis (Di Russo et al., 2003). Our present results show that the N1p component was significantly affected by TOT effect, including a decrease in its amplitude and an increase in its latency.

While increases in N1p latency in response to the TOT effect have never been investigated to date, decreases in its amplitude have been reported previously (Boksem et al., 2005; Faber et al., 2012). First, the increase in N1p peak latency may be related to an increase in the computational burden of the fronto-parietal network with TOT. Indeed, the fronto-parietal network has to increasingly deal with task-unrelated sources of information (*e.g.*, mind-wandering) as time elapses (Langner and Eickhoff, 2012); as a consequence, it might take more time for these areas to trigger neural feedback signals to the secondary visual cortices, hence delaying their reactivation. Second, the decrease in N1p amplitude suggests a weakening of the sensory gain mechanism of attention with TOT. As aforementioned, Weissman et al. (2006) reported a weakening of the event-related hemodynamic response of the secondary visual areas with TOT effect. The present finding of a reduction of N1p amplitude suggests that results by Weissman et al. (2006) might reflect an alteration of the late processing stage within the secondary visual areas. Impairment of N1p as a consequence of TOT effect supports the hypothesis of defective top-down modulation of visual cortex activity, which, we think, may partially explain the poor perceptual and behavioral performance associated with attention decrement.

Contrary to the TOT effect, temporal expectations did not affect the reactivation of visual areas, thought to be represented by N1p. It is worth noting that hierarchical predictive coding models, in their current form, do not account for such a reactivation of visual areas, which actually represents a later processing stage but at a lower level in the structural hierarchy as compared to N1a. Our study reveals that N1p was insensitive to the temporal expectations as elicited by the LC series of spatially fixed stimuli. Similar results have been reported using a probabilistic cueing paradigm by Miniussi et al. (1999). However, in contradiction of this assertion, Doherty et al. (2005) found an attenuation of N1p amplitude using a spatio-temporal task in which the movement of an object before its disappearance under an occluding barrier generated expectations of the timing of its reappearance. Then, the later processing stage supposed to manifest in reactivation of visual areas may be engaged in even higher-order temporal expectations, such as emerging from the operationalization of spatio-temporal rules. Future research on hierarchical predictive coding models might want to consider that such a later processing stage could occur at a lower structural level in vision when higher-order expectations are involved. Investigating the effect of attention decrement on such higher-order expectations represents a complementary interesting issue for future research, as both processes would alter the later processing stage reflected by the N1p component.

Conclusions

Overall, our study demonstrates the beneficial effect of temporal expectations on behavioral performance in response to fractal long-range correlated visual stimuli. The behavioral benefits associated with temporal expectations were independent of attention decrement, leading us to conclude that the construction of temporal expectations is not affected by changes in attention capacities. At the neural level, our results revealed that (*i*) the encoding of temporal expectations involved an intermediate processing stage, reflected by the N1a component, thus potentially engaging the intraparietal cortex, while (*ii*) the TOT effect selectively affected the later processing stage, reflected by the N1p component thought to represent a reactivation process of the secondary visual areas. Taken together, our findings provide evidence that the effects of temporal expectations and TOT induced in a single task can be independent at the behavioral level, and are supported at separate stages of information processing at the neural level in the visual domain.

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Classification of NIRS-measured hemodynamics of the cerebral cortex to detect lapses in attention.

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Introduction

Sustained attention is daily exploited by humans to carry out high order cognitive processes (Sarter et al., 2001). Crossing a busy area, driving for a long time or, in a more general manner, achieving goal-directed behaviours require the individual to increase and maintain a certain level of attention. Attention resources are finite and a certain degree of lapse in attention is usually observed during sustained attention tasks over a period of time. Given the substantial role of sustained attention in daily living tasks, such a decrease in the level of attention can incur serious consequences, including traffic accidents and work-related injuries (Czeisler et al., 2005). Being able to detect the occurrence of lapses in attention non-invasively might allow prevention of such aforementioned accidents.

To achieve this, one possibility lies in monitoring changes in brain activity accompanying the occurrence of lapses in attention. Electroencephalography (EEG) has been used for this purpose (e.g., Shen et al., 2008; Johnson et al., 2011). EEG signatures of attention decrements are well-identified and reproducible, and consist of an increase in low-frequency band power (theta band - 4 to 8 Hz) concomitant with a decrease in high-frequency band power (beta band - 13 to 30 Hz, Paus et al., 1997). Nevertheless, exploiting such features for classification purposes involves transformation from the temporal to the frequency domain (i.e., fast fourrier transform,) which is incompatible with the requirement of reducing the computational cost and algorithm complexity (Johnson et al., 2011). Moreover, the high sensitivity of EEG recordings to movement artefacts, electrocardiographic/electromyographic signals, and surrounding electrical noises represents another drawback that makes this technique still difficult to exploit for detection of lapses in attention under ecological conditions.

Near-InfraRed Spectroscopy (NIRS) could become an alternative technique for monitoring changes in the cortical activity that underly such decrements of attentional resources. Disposed over the scalp, optodes allow heo measurement of variations in concentration levels of oxyhemoglobin ([O_2Hb]) and deoxyhemoglobin ([HHb]) related to regional changes in neural activity. Compared to EEG signals, NIRS signals are relatively less sensitive to movement artifacts and are fully insensitive to electrical noises. As a result NIRS could be used during movement (Perrey, 2008) and could be thus more easily transferable from the laboratory to everyday living situations than EEG.

Furthermore, [O_2Hb] and [HHb] variations can be directly exploited in the temporal domain to classify changes in the cognitive state of individuals, as attested by several NIRS-based brain-computer interface studies (Coyle et al., 2004; Sitaram et al., 2007; Taï and Chau, 2009). In the present study, we aim at testing the applicability of using NIRS-measured cortical activity to classify whether subjects present - or do not present - lapses in attention during a specific sustained attention task.

Materials and Methods

Seven right-handed healthy subjects (aged 29.5±8.1 years) participated in this pilot study. The subjects were asked to sit at a table facing a lamp positioned at 1 m from the eye level. The right hand was held in the sagittal plane and fixed with straps. The thumb was fixed against a dynamometer allowing direct measurement of abduction force (Captels, Saint-Mathieu-de-Tréviers, France).

A simple visual RT (reaction time) task was performed during 1 min to familiarize the subjects with the paradigm. The visual stimulus consisted of lighting the lamp. The lighting epoch was 150 ms. The motor response to the visual stimulus consisted of thumb abduction. A randomly varying inter-stimuli interval was set (range 2 -15 sec). The subjects had then to rest for 2 min in order to stabilize the NIRS signals recorded over the cerebral cortex. This was followed by a sustained attention task of 30 min duration, whose characteristics were the same as those during the 1 min familiarization task. A scheme of the experimental design can be found in Figure 1.

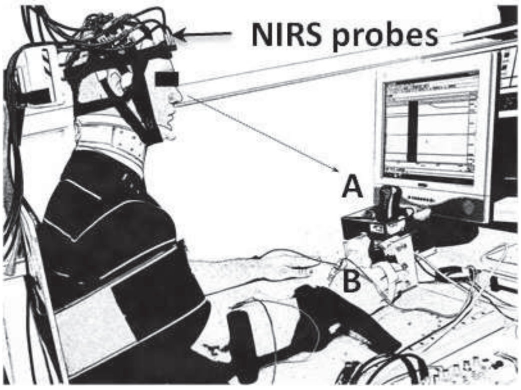

Figure 1: Experimental set-up.

A. Light source evoking the visual target stimuli during the sustained attention RT task. From the beginning of the task, subjects had to attend and prepare for the upcoming stimulus when the light source was off (i.e., during inter-stimuli intervals). Subjects were instructed that when a flash occurred they should generate a thumb abduction as quickly as possible. *B. Dynamometer allowing the measurement of the thumb abduction movements (i.e., the motor responses).* The reaction time was calculated as the difference between the onset of a motor response and the onset of the preceding flash stimulus.

NIRS measurements were performed using a continuous wave (CW) multichannel system (Oxymon Mark III, Artinis, The Netherlands). One channel consisted of a transmitter probe and a receiver probe. The inter-probe distance was 3.5 cm. Six channels were disposed over the scalp. Two were positioned over the frontopolar part of the right and the middle prefrontal cortex (rPFC and mPFC, respectively) and four over the right parietal area. The probes were placed according to the modified international EEG 10-10 system and mounted on a custom-made cap fixed by several bands surrounding the head of the subject. The NIRS probe design can be viewed in Figure 1. The CW system used in this study allowed measurement of changes in optical density at two different wavelengths in the near-infrared range (nominal wavelengths 763 and 855 nm) before converting them into changes in $[O_2Hb]$ and [HHb] in µM units. The sampling rate was set at 10 Hz. An example of a typical NIRS-measured cortical activation pattern is given in Figure 2.

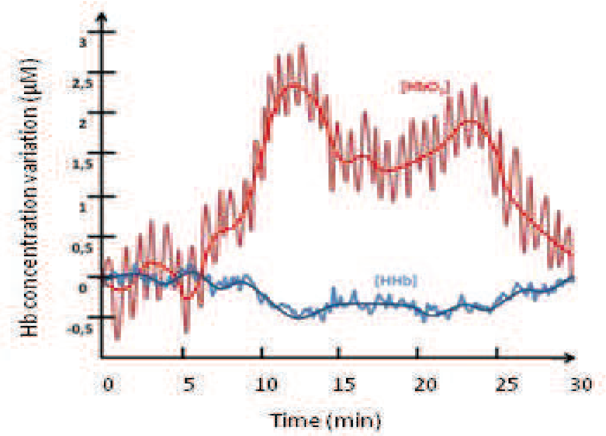

Figure 2: Typical NIRS-measured cortical activation pattern. Changes in optical density across time informed us about the local changes in oxy- and deoxy- hemoglobin concentrations (in µM). Two time series were recorded for each cortical area, resulting in a total of twelve time series (six task-relevant cortical areas have been investigated).

All of the classification procedure was performed off-line. The first step consisted of preprocessing the raw NIRS signals. The NIRS signals were initially filtered using a fourth order low-pass Butterworth filter and a cut-off frequency of 0.1 Hz in order to remove the heart rate and respiratory components (Huppert et al., 2009). Then, movement artifacts were removed on visually-identified specific channels by using moving standard deviation and spline interpolation (see Scholkman et al., 2010, for details). Finally, given that our data set contained information about the cortical hemodynamic changes over several regions of the brain and from many different subjects, a z-normalization of the signals was performed. From the resulting signals, the supervised classification procedure was performed by means of a support vector machines (SVM) algorithm. SVMs are supervised learning methods that aim at producing a model based on a training data set which predicts the classes of a test data set given feature values. To build such a model, training data points are mapped into a feature space so that classes are separated by a margin that must be as wide as possible. Test data are then mapped into the same feature space and classes are predicted according to the side of the margin to which the points belong (see Cortes and Vapnik, 199, for details). The Weka software (version 3.6.8, University of Waikato Hamilton, New Zealand) was used to perform classification analyses on our data. We designed the SVM for two-class classification analyses (i.e., no attention deficits versus attention deficits). Three classification analyses were performed exploiting the NIRS signals from (i) the 5 first and 5 last minutes of task, (ii) the 10 first and 10 last minutes of task and (iii) the 15 first and 15 last minutes of task. For each analysis, the NIRS signals from the first minutes of task were considered as characterizing the '*no attention deficits*' class, while the NIRS signals from the last minutes of task were considered as characterizing the '*attention deficits*' class (this assumption was then supported by analyzing the RT values as described below). The training data set consisted of the data obtained from 6 of 7 subjects and the test data set consisted of the data of the remaining subject. This procedure - so-called cross-validation - was repeated to test the classification accuracy for each of the seven subjects. Classification accuracy was calculated as the percentage of good classification of each signal sample for each part of the data (i.e., first or last minutes of task).

Mean RT were calculated for each subject over the following periods: (i) 5 first and 5 last minutes of task, (ii) 10 first and 10 last minutes of task and (iii) 15 first and 15 last minutes of task. Wilcoxon's T-tests were performed to test for any significant differences between RT values from the first and the last minutes of task. Finally, the increase in RT values from the first to the last minutes of task was calculated as a percentage of the initial RT for each subject and a Pearson linear regression was performed to test for any relationship between the relative increase in RT over time and the performance with regard to the supervised classification (i.e., classification accuracy results). By doing so, we aimed at testing whether subjects presenting the highest increase in RT across time, that is, the stronger decrement of attention, presented better classification accuracy results or not. The significant threshold for statistical analyses was set at $p < .05$.

Results and discussion

The detailed results of the classification accuracy are given in Table 1.

Subject	5 first / 5 last min	10 first / 10 last min	15 first / 15 last min
1	88.2	88.2	84.8
2	97.3	82.3	73.3
3	76.0	62.3	76.5
4	98.0	84.2	72.9
5	67.8	77.7	77.4
6	99.2	92.1	76.9
7	89.6	92.5	80.7
Mean	**88.0**	**82.7**	**77.5**
SD	12.0	10.0	4.0

Table 1: Individual and mean values of the classification accuracy for each analysis. Classification accuracy values are given in percentage of total classification trials (with one trial corresponding to one sample of the NIRS signals). The second, third and fourth columns present the two-classes classification results by exploiting (i) the 5 first and last minutes of task, (ii) the

10 first and last minutes of task and (iii) the 15 first and last minutes of task, respectively.

Wilcoxon's T-tests revealed significant differences between mean RT values from the 5 first and the 5 last minutes of task (p = .02) and from the 10 first and the 10 last minutes of task (p = .04). No significant difference was found between the mean RT from the 15 first and the 15 last minutes of task (p = .09). This result is presented in Figure 1.

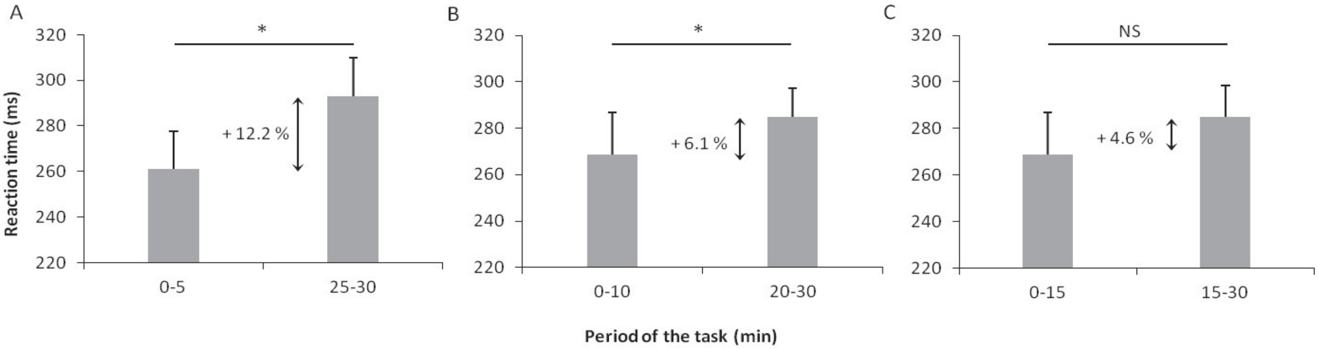

Figure 3: Changes in mean RT values from the first to the last minutes of the 30 minutes duration sustained attention task. Differences have been tested between (A) the 5 first and last minutes of task, (B) the 10 first and last minutes of task and (C) the 15 first and last minutes of task. Vertical bars represent SD. * p < . 05.

Pearson's correlation showed a significant positive linear relationship between the percentage of RT increase and the performance of the classifier in terms of accuracy (Figure 2).

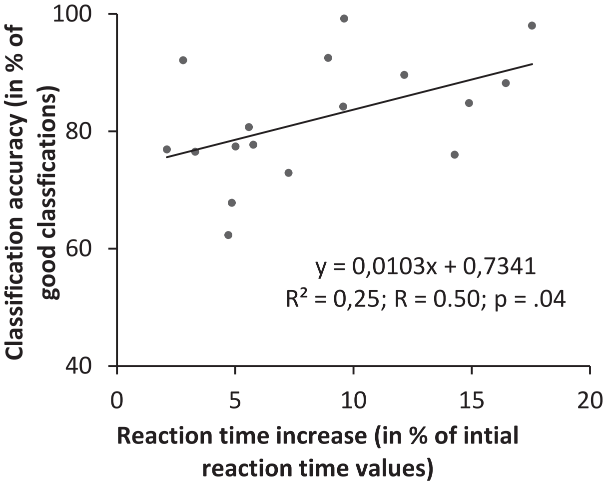

Figure 4: Relationship between classification accuracy and relative increase in reaction time. Each point represents the result for one subject as regards to the classification accuracy and the increase in RT.

In the present study, the objective was to test the applicability of using NIRS-measured cortical activity in order to classify whether subjects presented - or did not present - lapses in attention during a specific sustained attention task. The results reported in this paper must be considered as preliminary and are encouraging for future analyses, including unsupervised classification. We showed that the classification accuracy was up to 80 % when a significant increase in RT could be statistically appreciated. Furthermore, a significant relationship between classification accuracy and relative increase in RT was revealed. These findings are examined in detail next.

As expected, classification accuracy was better when the 5 first and last minutes of NIRS signals were exploited than when the 10 first and last - or even moreso, the 15 first and last minutes of signals - were. Such a result could be considered as intuitive, since the largest differences in the level of attention, and therefore the largest changes in cortical activity, are expected to occur between the very beginning and the very end of the task.

This finding agreed with independent EEG studies reported in the literature. For instance, Trejo et al. (2006) found a very high percentage of classification accuracy - ranging from 91 % to 100 % - while Shen et al. (2008) found a mean percentage of classification accuracy of 85.4 % by using the same classifier (i.e., standard SVM) and EEG features (i.e., frequency band power).

The difference in classification accuracy found in these studies resides in the signal epochs exploited to perform the classification, with regards to the duration of the total recording. While the former authors used the 15 first and last minutes of a 3 hours duration sustained attention task, the latter separated the data into five epochs that originated from continuously recorded EEG signals. Our "5 first/5 last minutes of task" classification test could be comparable to the analysis performed by Trejo et al. (2006) whereas the "15 first/15 last minutes of task" classification test could be more related to the one realized by Shen et al. (2008). RT results supported the assumption that a decrease in the level of attention occurred during the sustained attention task and that stronger differences were present during the very beginning and the very end of the task. Taken together, these results suggested that the stronger the attentional decrement, the better the classification accuracy. This result was further reinforced by the significant positive linear relationship found between the relative increase in RT and the classification accuracy. Roughly, Figure 2 indicates that when RT increases from 0 to 8 % of the initial RT value only, the classification accuracy did not go beyond 80 %, while when the RT increased from 10 to 20 % of the initial RT value, the classification accuracy exceeded 80% most of time. In other words, when behavioural results barely indicate a decrease in the level of attention, the changes in NIRS signals become more difficult to distinguish through a supervised classification analysis. It could be relevant in the future to go beyond a strictly binary classification analysis (i.e., searching for two classes) and to further consider the potential presence of several levels in the attention decrement, depending on subjects' cognitive resources. This would the subjects with a slower decrease in attentional resources to be classified by steps from a state of "no attentional deficits" to a state of "attentional deficits". Additionally, future researches in the field should aim at monitoring the level of attentional decrement by giving a probability of belonging to one of the classes for each sample of the NIRS signals, rather than giving a strict decision about their membership. Probabilistic multi-classes SVMs (Shen et al., 2008) and fuzzy clustering analyses (e.g., fuzzy c-means) could address the two aforementioned purposes.

Conclusion

These preliminary results contribute to consider the potential exploitation of the NIRS-measured hemodynamic signals of the cerebral cortex to detect lapses in attention. We bring the first evidence that NIRS has good potential to monitor attention deficits. Our results suggest that future work should involve (i) multi-classes and (ii) probabilistic or fuzzy classification analyses to better monitor the time course of attentional resources across time.

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Appendix B

Appendix B is comprised of two selected peer-reviewed articles to which I contributed but which were not directly related to this thesis.

Article 1

Published as: **Derosiere G**, Alexandre F, Bourdillon N, Mandrick K, Ward TE, Perrey S. (2014). Similar scaling of contralateral and ipsilateral cortical responses during graded unimanual force generation. *NeuroImage*, *85*, 471-477.

Article 2

Published as: Dalhoumi S, **Derosiere G**, Dray G, Montmain J, Perrey S. (2014). Graph-based transfer learning for managing brain signals variability in NIRS-based BCIs. *Proceedings of the 15th International Conference on Information Processing and Management of Uncertainty. A. Laurent et al. (Eds.): IPMU 2014, Part II, CCIS 443, pp. 294–303, 2014. © Springer International Publishing Switzerland 2014*

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Similar scaling of contralateral and ipsilateral cortical responses during graded unimanual force generation

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ABSTRACT

Hemibody movements are strongly considered as being under the control of the contralateral hemisphere of the cerebral cortex. However, some neuroimaging studies have found a bilateral activation of either the primary sensori-motor (SM1) areas or the rostral prefrontal cortex (PFC), during unimanual tasks. More than just bilateral, the activation of these areas was found to be symmetrical in some studies. However, the symmetrical response remains strongly controversial notably for handgrip force generations. We therefore aimed to examine the bilateral SM1 and rostral PFC area activations in response to graded submaximal force generation during a unilateral handgrip task. Fifteen healthy subjects performed 6 levels of force (ranging from 5 to 50% of MVC) during a handgrip task. We concomitantly measured the activation of bilateral SM1 and rostral PFC areas through near-infrared spectroscopy (NIRS) and the electromyographic (EMG) activity of the bilateral flexor digitorum superficialis (FDS) muscles. Symmetrical activation was found over the SM1 areas for all the investigated levels of force. At the highest level of force (i.e., 50% of MVC), the EMG of the passive FDS increased significantly and the ipsilateral rostral PFC activation was found more intense than the corresponding contralateral rostral PFC activation. We suggest that the visuo-guided control of force levels during a handgrip task requires the cross-talk from ipsi- to contralateral SM1 to cope for the relative complexity of the task, similar to that which occurs during complex sequential finger movement. We also propose alternative explanations for the observed symmetrical SM1 activation including (i) the ipsilateral corticospinal tract and (ii) interhemispheric inhibition (IHI) mechanism. The increase in EMG activity over the passive FDS could be associated with a release of IHI at 50% of MVC. Finally, our results suggest that the greater ipsilateral (right) rostral PFC activation may reflect the greater demand of attention required to control the motor output at high levels of force.

Introduction

The corticospinal tract (CST) is classically depicted as a crossed pathway and subsequently hemibody movements are often considered as emanating from under the control of the contralateral hemisphere of the cerebral cortex. However, the true nature of the CST is more complex, this structure not being a fully crossed pathway (Kuypers, 1985). Those nervous fibers not crossing constitute the ipsilateral CST. Numerous authors have described the role of the latter in the control of unilateral hand tasks (Bawa et al., 2004; Brus-Ramer et al., 2009; Wassermann et al., 1991, 1994; Ziemann et al., 1999) and have implicated ipsilateral cortical activation in unimanual control through neuroimaging methods. For instance, Wriessnegger et al. (2008) reported, using the near-infrared spectroscopy (NIRS) technique, a bilateral activation over the primary sensorimotor (SM1) areas during a unilateral finger tapping task, as revealed by an increase in oxyhemoglobin (O_2Hb) and a slight decrease in deoxyhemoglobin (HHb). Similarly, Pfurtscheller et al. (2000) found a bilateral electroencephalography (EEG)-measured event-related desynchronization in the lower mu-rhythm during unimanual movement compared to rest.

Whereas the presence of ipsilateral cortical involvement in unimanual tasks is clearly supported through previous studies the extent or magnitude of this relation has still not been definitively established. On the one hand, numerous studies describe the response of the SM1 areas as asymmetric (Catalan et al., 1998; Ehrsson et al., 2000; Kawashima et al., 1996; Tanji et al., 1988), and favor a higher contralateral activation for a large panel of hand tasks. On the other hand, no significant difference between the ipsilateral and the contralateral

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activations of these areas were found during complex sequential finger movements (Verstynen et al., 2005). The high magnitude of the ipsilateral SM1 area activation was related to the role of this area in “shaping precisely” the muscular command originating from the contralateral hemisphere (Davare et al., 2007; Ehrsson et al., 2000) when fine finger control is required. Indeed, according to the transcranial magnetic stimulation study performed by Davare et al. (2007), during unimanual fine finger movements the ipsilateral M1 strongly contributes to the setting of muscle recruitment timing, either through facilitatory or inhibitory mechanisms. In summary, traditional neuroimaging data show that tasks involving a higher complexity in the sequencing of finger movements elicit stronger and less asymmetric activation pattern in motor areas. Nevertheless, similar results were found with functional magnetic resonance imaging (fMRI) for the production of various submaximal levels of force in power-handgrip tasks (Dai et al., 2001), a task which does not require much precision according to phylogenetic and functional considerations (Ehrsson et al., 2000; Napier, 1956). Indeed, based on the findings from Dai et al. (2001), albeit not highlighted by the authors, one may observe a symmetrical activation of the SM1 areas from 20 to 65% of maximal voluntary contraction (MVC) during a handgrip task. Further, Shibuya et al. (2008) found a NIRS-measured symmetrical M1 activation during the course of a low-intensity fatiguing handgrip task.

It is possible that this symmetrical activation pattern may not be limited to the SM1 areas only. The rostral prefrontal cortex (PFC) areas for example, are ipsilaterally connected to the motor areas through cortico-cortical pathways (Krieghoff et al., 2011) and are involved in the initiation and the control of voluntary movements (Miller and Cohen, 2001). A bilateral activation of the rostral PFC areas has been observed during fatiguing unilateral handgrip tasks (Liu et al., 2003; Mottola et al., 2006). However, the involvement of processes associated with fatigue in these studies and in Shibuya et al. (2008) may obscure the true extent of such bilateral activation. Finally, while previous studies have reported a symmetrical activation of the SM1 areas during various submaximal levels of force (Dai et al., 2001), the corresponding result for the rostral PFC has not been reported to date.

Therefore, we aim to examine the ipsilateral and contralateral activation responses of SM1 and rostral PFC areas to graded levels of force production during a unilateral handgrip task. We suggest that the symmetrical activation observed is not a property of the complex sequential finger movements only. Rather, in accordance with the results of Dai et al. (2001), we hypothesize that contralateral and ipsilateral rostral PFC and SM1 changes operate in a similar way with graded submaximal force generation during a unilateral handgrip task. The new insight revealed by this study may be relevant for the diagnostic evaluation of neurological hand motor assessments. Such a NIRS method could be used to examine the cortical activation during the assessment and at the same time monitor treatment progress with less strenuous procedures than traditional neuroimaging methods (fMRI and EEG).

Materials and methods

Participants

Fifteen healthy volunteers took part in the study (aged 28.0 ± 7.5 years; height 175.5 ± 5.9 cm; body weight 69.4 ± 8.9 kg). All subjects were right-handed according to the Edinburgh Questionnaire (Oldfield, 1971). None had any sign of neurological, respiratory, and cardiovascular disease or used medication, which might affect brain and muscle functions. Each subject provided written informed consent prior to participation in the study. All procedures were approved by the local ethics committee (CPP Sud-Méditerranée II, number 2010-11-05) and complied with the Declaration of Helsinki for human experimentation.

Protocol and task procedure

The experiments were conducted in a quiet and dimly lit room. Each subject performed the entire protocol once. The subjects were asked to sit comfortably at a table. They were facing a computer screen with the left forearm resting upon the surface and held in place with straps to prevent extraneous movements during isometric contractions of the right forearm. The dominant hand was held in neutral position in the sagittal plane. The angle of the elbow was set to 110° for each subject (with 0° corresponding to the full extension of the arm). The protocol began with a familiarization and warm-up phase with the handgrip task. After individual set-up, the subjects were requested to perform during 5 min a few static submaximal contractions of the finger flexors in an intermittent mode. Foremost, the subjects produced three MVCs of a 5-s duration followed by 90 s of passive recovery. Second, each subject underwent an experimental block-paradigm design containing six conditions of static submaximal force levels repeated three times. The target levels of force were set at 5%, 10%, 20%, 30%, 40% and 50% of MVC. The subjects matched their force with a target force for 30 s followed by 60 s of rest. Applying such intervals in the set-up was determined following pilot trials to both maximize NIRS-evoked responses and minimize the occurrence of neuromuscular fatigue. The block paradigms were pseudo-randomized to avoid order and fatigue effects as well. The pseudo-random order prevented immediate repetition of relatively high force levels between conditions and blocks. Immediately after each block, a MVC was carried out to ensure that no neuromuscular fatigue was induced by the successive muscle contractions. To reduce artifacts, the subjects were asked throughout the experimental protocol to minimize head and body movements as well as to breathe as gently and as regularly as possible.

Measurements

Force

The levels of force were recorded using a handgrip dynamometer (Captels, Saint-Mathieu de Tréviers, France). The force signals were recorded at 1000 samples per second using a data acquisition system (Biopac MP30, System Inc., Santa Barbara, CA). To maintain the level of force correctly, visual feedback was displayed on the computer screen facing the subjects.

Electromyography

The surface electromyogram (sEMG) of the flexor digitorum superficialis (FDS) muscle of the hand actively involved in the task (right) and the passive (left) hand were recorded using bipolar Ag/AgCl electrodes (Contrôle Graphique Medical, Brie-Comte-Robert, France) with a 9-mm diameter at an inter-electrode distance of 20 mm. The skin was shaved, abraded and washed with emery paper and cleaned with 70° alcohol in order to obtain low impedance between the two bipolar electrodes (<3 kΩ). The reference electrode was positioned on the styloid process of the left ulna. The EMG cables were strapped to the chair to prevent movement artifacts. The EMG signals were amplified (×1000), measured at a sample rate of 1000 samples per second and synchronized with the force signals using the Biopac MP30 data acquisition system (Biopac System, Inc., Santa Barbara, CA).

Near infrared spectroscopy

The NIRS technique has been described elsewhere (Elwell et al., 1994) and has been demonstrated previously as relevant for investigating cortical activity during movement generation (Perrey, 2008). NIRS measurements were performed using a continuous wave (CW) multichannel NIRS system (Oxymon Mk III, Artinis, The Netherlands). The sampling rate was set at 10 Hz. This system allowed measurement of changes in optical density at two different wavelengths in the near-infrared range (nominal wavelengths 760 and 850 nm) before converting them into changes in concentration of [O_2Hb] and [HHb]. A subject-specific differential path length factor (DPF) was used for this conversion based on the age of each subject (Duncan et al., 1996). This allowed measurement of the concentration changes of [O_2Hb] and [HHb] in μM unit (Delpy et al., 1988). The inter-probes distance was set to 3.5 cm. In the present study, the measurements were performed using 10 channels positioned over the SM1 and the rostral PFC areas (Fig. 1) according to the modified international EEG 10–10 system (AES, 1994). The probes were mounted on a custom-made cap fixated by several bands surrounding the head of the subject. In order to check the positions of the probes around the motor areas, the subjects were asked to perform a short sequence of rhythmic movements of the contralateral hand to induce a hemodynamic response. If no oxygenation change occurred, the probes were moved several millimeters until, by trial and error, a consistent oxygenation response was obtained. During the placement of the probes, the Oxysoft software (V6.0, Artinis, The Netherlands) allowed real time assessment of the quality of the NIRS signal for each channels based on the light source power level and the receiver gain. In order to demarcate the stimulus periods (i.e., presentation of target force levels), specific events were set indicating the task and rest periods in each block.

Data analysis

Force levels

For each subject, the average of the three peak-to-peak amplitudes calculated within a 2-second time window during MVCs was considered as the maximal voluntary force. Target forces in % MVC were computed subsequently for each subject. After the experimental procedure, each level of desired force was re-calculated over the last 20 s of force production to check if the subjects followed the task requirement.

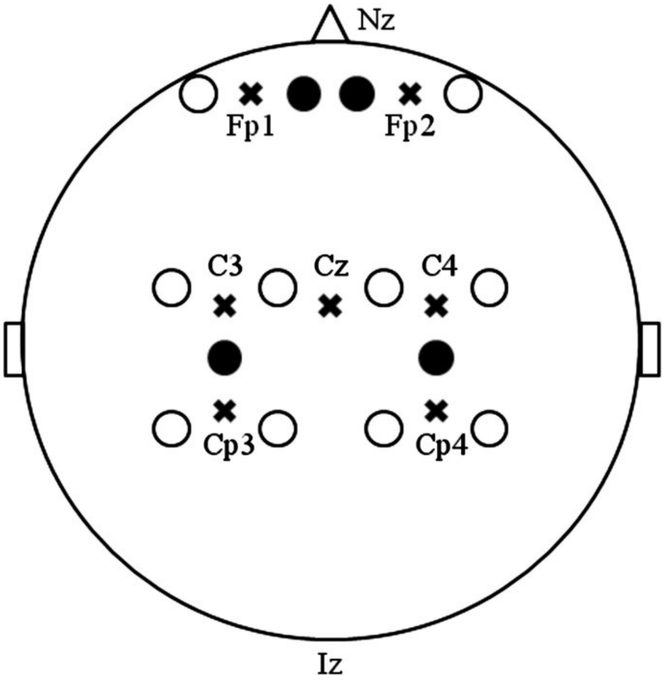

Fig. 1. NIRS probes placement. Each SM1 area was explored by the mean of 4 emitters (empty circles) and one receiver (black circles). The receivers were placed over the contralateral and the ipsilateral SM1 areas according to the modified international EEG 10–10 system between the C3 and the Cp3 points, and the C4 and the Cp4 points, respectively. Each rostral PFC area was explored by the mean of one emitter and one receiver. The midway between the receivers and the emitters were placed over the Fp1 (contralateral side) and Fp2 (ipsilateral side) points. This placement, resulting in a total of 10 channels, allowed measurement of the activation over the contralateral and ipsilateral SM1 and rostral PFC areas.

Electromyography

The raw sEMG signals were band-pass filtered (30–500 Hz) before a root mean square (RMS) measure was calculated over the last 20 s of force production for each target force. This processing was performed using scientific computing software (Scilab 5.3, Consortium Scilab, INRIA-ENPC, Paris, France).

Near infrared spectroscopy

Dedicated NIRS analysis software was used to obtain [O_2Hb] and [HHb] signals. The raw data were processed offline using the Oxysoft analysis program (V6.0, Artinis, The Netherlands) developed with the multichannel NIRS Oxymon Mk III system. The first step consisted of a visual analysis incorporating pre-processing. This aimed to delete the specific channel where large movement artifacts had occurred or where the signal-to-noise ratio was too low. Then, the NIRS raw data were low-pass filtered using a cut-off frequency of 0.7 Hz in order to remove the heart rate signal (Huppert et al., 2009). Finally, the data were block averaged and detrended (to eliminate slow drifts) to obtain a grand-average evoked response for each level of force. From the resulting individual signals, the averages of the last 20 s of each resting period preceding the stimulation period under consideration were subtracted from the averages of the last 5 s of each stimulation period (Colier et al., 1999). This analysis resulted in deltas, noted Δ[O_2Hb] and Δ[HHb]. For each level of force, the Δ[O_2Hb] and Δ[HHb] for the four channels over the SM1 areas were averaged together resulting in an overall SM1 response. In order to determine left/right asymmetry of rostral PFC and SM1 activity during the handgrip tasks, a laterality index for Δ[O_2Hb] changes was calculated for each level of target force, as follows: (*left side − right side*)/(*left side + right side*) (Cramer et al., 2002; Lee et al., 2000).

Statistical analysis

Statistica software (version 7.0, Statsoft, Oklahoma, United-States) was used for all analyses. All data were examined for normality and homogeneity using Skewness–Kurtosis and Levene tests, respectively. A two-way repeated measures ANOVA was used to test for any significant effect of the hemisphere side (ipsilateral, contralateral) and the level of force (5, 10, 20, 30, 40, 50% of MVC) on the changes in Δ[O_2Hb] and Δ[HHb] over the SM1 and the rostral PFC areas. When appropriate, the Tukey's HSD post-hoc test was used to detect paired differences. A student's *t*-test for paired samples was used to test for difference between the predicted and the measured levels of force. Because of the non-normal distribution of the EMG RMS and MVC samples, non-parametric tests have been applied on these data. Friedman ANOVAs were performed to test for the significant effect of the level of force on the laterality index and the EMG RMS values. Similarly, Friedman ANOVA was performed to test for any change in the MVC values between each block. When appropriate, the Conover post-hoc test was used to detect paired differences. The significance level was set at $p<.05$. Data are presented mean ± standard deviation (SD) unless specified.

Results

MVC and target force levels

A Student's *t*-test for paired samples ensured that there was no difference between predicted and measured levels of force ($t = 0.04$, $p = .96$). The MVCs realized after each block were 260.8 ± 67.1 N, 269.6 ± 64.8 N and 262.7 ± 70.6 N and were not significantly different from one another ($Fr_{15,\,2} = 1.6$, $p = .45$).

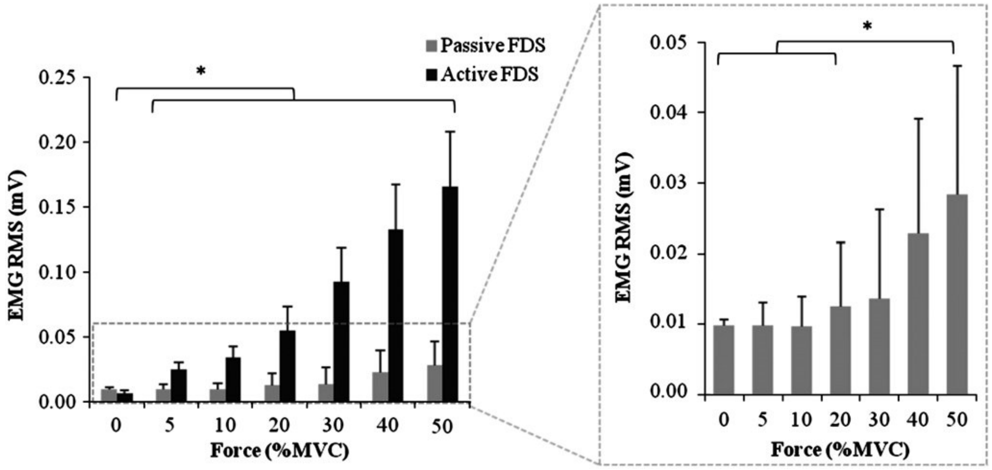

Fig. 2. Electromyographic activity (EMG) of the flexor digitorum superficialis (FDS) muscle during handgrip tasks. Change in EMG activity (RMS values) of the passive and active FDS is expressed for each level of force (% MVC). On the right, the results of the passive FDS have been enlarged. * Significant effect of the level of force at p<.05. Vertical bars represent SE.

Electromyography

A significant increase in EMG RMS values was observed as a function of the force levels in both the active ($Fr_{15,6} = 84.21$; $p < .001$) and passive FDS ($Fr_{15,6} = 31.25$; $p < .001$). The Conover post-hoc tests indicated a significant increase in the EMG RMS of the active FDS beyond 10% MVC ($p < .05$) and a significantly higher EMG RMS of the passive FDS at 50% MVC compared to 0, 5, 10 and 20% of MVC was found ($p < .05$; Fig. 2).

Cortical activation and force

All trials were similar in terms of cortical activation response, typically expressed as an increase in [O_2Hb] and a slight or no decrease in [HHb] (Hirth et al., 1996; Obrig et al., 2000). However, because of motion artifacts and a low signal-to-noise ratio in some cases, 7.1% of the SM1 signals and 21.6% of the rostral PFC signals were removed from the analysis.

Changes in the contralateral and ipsilateral SM1 areas

A significant increase in Δ[O_2Hb] with the increased levels of force ($F_{5,60} = 14.26$, $p < .001$) was observed over the SM1 areas but there was no difference according to the hemisphere side ($F_{1,12} = 3.90$, $p > .05$). Post-hoc tests indicated a significant increase in Δ[O_2Hb] between 30, 40, 50% of MVC and 5% of MVC and 40 and 30% of MVC. No difference in Δ[O_2Hb] was found between 40 and 50% of MVC on both hemispheres. A significant increase in Δ[HHb] with the increased level of force ($F_{5,65} = 6.35$, $p < .001$) was also observed with no change with respect to the hemisphere side ($F_{1,13} = 3.23$, $p = .09$). Post-hoc tests indicated a significant increase in Δ[HHb] beyond 40% of MVC on both hemispheres. These results are presented in Fig. 3.A.

Changes in the contralateral and ipsilateral rostral PFC areas

A significant interaction of force level × hemisphere was found in Δ[O_2Hb] ($F_{5,45} = 3.29$, $p < .05$). Post-hoc tests indicated significant increase in Δ[O_2Hb] between 30, 40, 50% of MVC and 5% of MVC, 40 and 30% of MVC and 50 and 40% of MVC in both sides. A significant difference in Δ[O_2Hb] was found between the contralateral and the ipsilateral rostral PFC at 50% MVC ($p < .001$). Δ[HHb] increased significantly with the increased level of force ($F_{5,20} = 12.01$, $p < .001$) but with no difference between the two hemispheres ($F_{1,4} = 0.29$, $p = .62$). Post-hoc tests indicated a significant increase in Δ[HHb] beyond 40% of MVC on both hemispheres. These results are presented in the Fig. 3.B.

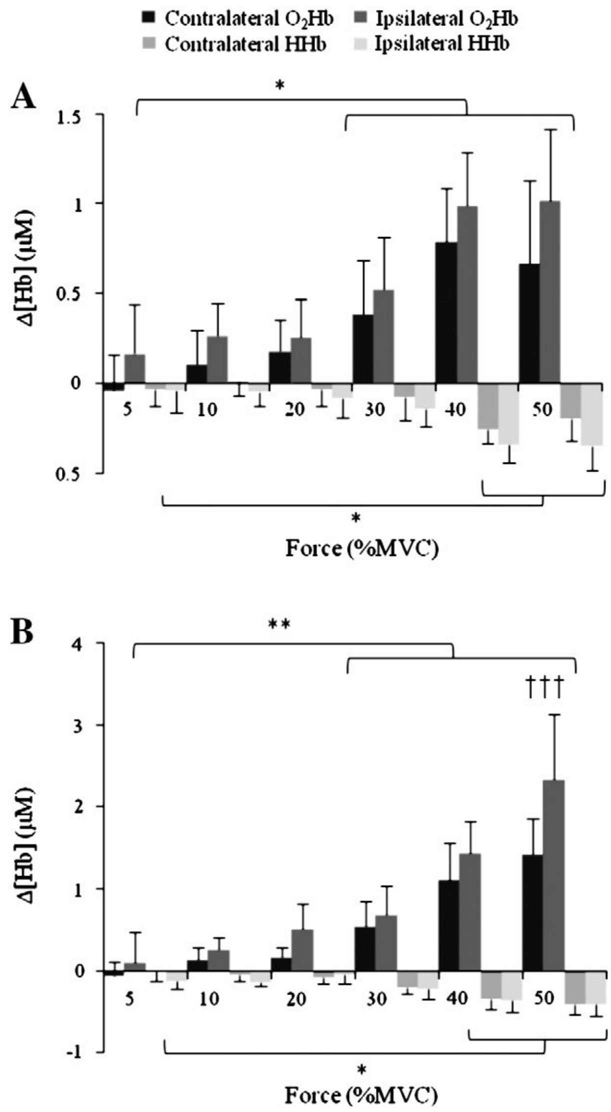

Fig. 3. Cortical activation during handgrip tasks. Changes in the contralateral and ipsilateral SM1 (A) and rostral PFC (B) areas are expressed for each level of force (% MVC). Significant effect of the level of force *p<.05, **p<.01. Significant effect of the hemisphere: †††p<.001. Vertical bars represent SE.

Laterality indexes

No significant difference was found between the laterality indexes of the SM1 areas for each level of target force ($Fr_{14,5} = 2.27$, $p = .81$). Due to the removal of some rostral PFC data, the calculation of the laterality indexes for this area was performed on 9 subjects. No significant difference was found between the laterality indices of the rostral PFC areas for each level of force ($Fr_{9,5} = 3.37$, $p = .62$).

Discussion

The aim of this study was to highlight the responses of the ipsilateral and contralateral SM1 and rostral PFC areas for graded levels of force during a unilateral handgrip task. We found that, at increasing levels of handgrip force from 5 to 50% of MVC, (i) the cortical activation responses over the SM1 areas did not differ between the contralateral and ipsilateral hemispheres while (ii) the rostral PFC activation was significantly higher on the ipsilateral side at the highest force (i.e., 50% of MVC); (iii) there was a significant increase in the EMG activity of the passive arm when producing 50% of MVC. These findings are examined in detail next.

Changes in the SM1 areas' activity

First of all, it is notable that all the investigated areas showed a significant cortical activation in producing static force beyond 30% of MVC. These results corroborate with earlier studies that investigated the relationship between the levels of force and the cortical activation either using NIRS (Derosiere and Perrey, 2012) or fMRI (Thickbroom et al., 1998) techniques. Further, the lack of significant increase in contralateral cortical activity at low levels of force has been previously described in primates (Cheney and Fetz, 1980; Georgopoulos et al., 1992) and humans (Ludman et al., 1996).

A second observation of note was that SM1 activation reached a plateau at around 40% of MVC. A similar result was found by Mima et al. (1999) who showed a decrease in the EEG signal power in the beta band between 40 and 60% of MVC, and between 60 and 80% of MVC. This prompts the interesting question as to: how is the production of a higher EMG output possible if the contralateral SM1 area activation remains stable or even decreases between 40 and 50% of MVC? We suggest that the secondary motor areas could participate in producing the increased drive required for higher levels of force. Indeed, according to Dum and Strick (2002), these areas have direct connections with spinal motoneurons, particularly those innervating hand muscles, and may therefore directly generate motor command during a handgrip task.

A third result of interest is that the ipsilateral SM1 area was found to be activated to the same degree as the contralateral SM1 area at all investigated levels of force. This result is further reinforced by the absence of modification of the laterality index at increasing levels of force and strongly supports the findings of Dai et al. (2001). Also, this result is in line with the symmetrical M1 activation found during the course of a low-intensity fatiguing handgrip task in the study of Shibuya et al. (2008). We do stress here a central issue of the present study. Symmetrical cortical activation is not restricted only to complex sequential finger movements but also occurs during static handgrip contractions. Nonetheless, the symmetrical SM1 activation occurrence in response to unilateral handgrip tasks may be subject to certain conditions. Some authors have failed to find symmetrical SM1 activation either during power-handgrip tasks (Cramer et al., 2002) or during simple finger tapping tasks (Durduran et al., 2004; Obrig et al., 1996). Differences between studies likely rely on the nature of the experimental setting associated to the task. In the present study and in the studies of Dai et al. (2001) and Shibuya et al. (2008) the handgrip tasks consisted in tracking a line by focusing on a screen in real time conditions. Such visual feedback was not given in the investigations by Cramer et al. (2002), Obrig et al. (1996) and Durduran et al. (2004). By comparing the fMRI-measured brain activity in subjects performing a visuo-guided handgrip task versus a non-guided handgrip task, Kuhtz-Buschbeck et al. (2008) compellingly evidence emerges that performing a visuo-guided handgrip task involves the activity of many additional areas, such as the ipsilateral SM1. In similar vein, Davare et al. (2007) demonstrated that the disruption of ipsilateral M1 activity by means of transcranial magnetic stimulation during a visuo-guided pinching force production altered dramatically the maintenance of the level of force. As mentioned in the introduction, the authors concluded that the ipsilateral M1 area has a role in “shaping precisely” the muscular command originating from the contralateral hemisphere. We propose that a visuo-guided handgrip task requires such a cross-talk between ipsilateral and contralateral SM1 areas. Further, given the linear relationship between force variability and force production (Missenard et al., 2008), at increasing force levels the force output might require significant control to match with the visual target, probably involving an increasing engagement of the ipsilateral SM1 area to shape the muscular command. Otherwise, as underlined by van Wijk et al. (2012), the ipsilateral M1 activity does not only result from cross-talk between hemispheres aiming at driving the muscular command. Rather, van Wijk et al. (2012) suggested that the ipsilateral and contralateral M1 activity may have distinct roles. We proposed thereafter two potential explanations of the symmetrical activation of the SM1 areas during unimanual handgrip tasks.

First, it can be speculated that the ipsilateral CST acted in the performed task to shape the intended levels of force. In this case, the higher number of excitatory post-synaptic potentials (PSP) onto the pyramidal neurons of the ipsilateral SM1 area would finally generate action potentials throughout the ipsilateral CST. However, the ipsilateral CST constitutes only five to six percent of the total of CST nervous fibers (Brosamle and Schwab, 1997). Therefore, it can be assumed that the number of excitatory PSP within the ipsilateral SM1 area would be reduced compared to those within the contralateral SM1 area and consequently the involvement of the ipsilateral CST cannot alone explain the symmetrical activation of the SM1 areas.

The second explanation concerns the occurrence of interhemispheric inhibition (IHI). The IHI is a mechanism responsible for the inhibition of mirror movements of the passive limb during unilateral hand movements (for a review, see Kicic et al., 2008). It is believed that the IHI consists of the depolarization of trans-colossal glutamatergic nervous fibers originating in the contralateral SM1, which consequently depolarize inhibitory inter-neurons within the ipsilateral SM1 area. These inter-neurons in turn inhibit the pyramidal neurons projecting to the contralateral arm (i.e., the passive arm). It is interesting to note that we observed a tendency of the ipsilateral SM1 area to be more activated than the contralateral SM1 area (Fig. 3), although this effect did not reach statistical significance. Based on this viewpoint, it can be supposed that the summation of the excitatory PSP from the trans-colossal nervous fibers and the inhibitory PSP from the inter-neurons is the cause of the stronger ipsilateral activation. More precisely, the IHI was found higher when performing 1 to 2% of MVC than when performing 20 to 40% of MVC during a pinch grip task (Liepert et al., 2001). Therefore, the reasoning provided above as regards to the potential role of the IHI in increasing the ipsilateral SM1 area activation is more valid in the interpretation of the symmetrical cortical activation occurring below 20% of MVC and not above this level of force. This result is further reinforced by considering the relative stability of the EMG activity of the passive FDS below 20% of MVC.

Changes in the rostral PFC areas' activity

We argue in the introduction that the rostral PFC areas should be symmetrically activated with increasing levels of force because they are ipsilaterally connected to the motor areas through cortico-cortical pathways (Krieghoff et al., 2011) and involved in the initiation and the control of voluntary movements (Miller and Cohen, 2001). Contrary to the SM1 areas, the difference between the activation of the ipsilateral and the contralateral rostral PFC areas reached statistical significance at 50% of MVC, in favor of a more intense ipsilateral activation. A hypothesis to explain this result is that the ipsilateral rostral PFC area (the right rostral PFC in the present study) was more activated because of the sustained attention required to perform the task. The right rostral PFC area is well-known to be responsible for the control of sustained attention (Sturm and Willmess, 2001). In similar vein, Okamoto et al. (2004) found a right-sided increase in rostral PFC activation during a complex manual task requiring attentional control (i.e., task consisted of peeling an apple) and suggested an involvement of the executive functions to perform the task. We suggest that the visuo-guided motor task contained in our protocol which required that the subject precisely maintained a target on the screen over a 30 s period involved a high level of sustained attention.

Changes in EMG activity

As has been described in the literature (e.g., Woods and Bigland-Ritchie, 1983), the EMG activity of the muscles involved in the task (i.e., the ipsilateral FDS) increases proportionally to the force produced during the isometric contractions. In terms of the EMG activity of the passive FDS measured in this study, a significant increase was found at 50% of MVC (Fig. 2). A similar result was found by Van Duinen et al. (2008) at 70% of MVC and can be linked to the study of Liepert et al. (2001) cited above who showed a lower IHI when increasing the level of force. These authors interpreted the occurrence of stronger IHI during unilateral hand movements at low levels of force as linked to the need to improve the dexterity during fine finger movements. They hypothesized that the inhibition of ipsilateral pyramidal neurons would therefore reduce the risk of interference of both hands, improving therefore the precision during handling of objects. According to this hypothesis about the role of the IHI during the production of higher levels of force, we suggest that the nervous system would adapt itself and would consequently not inhibit the passive arm explaining the occurrence of “mirror” contractions of the FDS at 50% of MVC.

Study limitations

Although the present study revealed interesting results on the bilateral activation patterns related to the control of submaximal force generation, it was nevertheless subject to a number of limitations. First, a potential limitation may be related to the anatomical positioning of the optodes. As most studies did, we used the international 10–10 system for EEG recordings (and skull surface landmarks) to localize the target cortex and position the NIRS optodes. Subsequently, functional oxygenation was controlled by executing a simple task to reveal hemodynamic responses. If no hemodynamic change was detected, the optodes were moved several millimeters and the task was executed again. In the present study, this was repeated until a consistent hemodynamic response was found (Shibuya et al., 2008). Also, we focused on decreases in [HHb] to ensure the correct location of the channel (Kleinschmidt et al., 1996). The location of NIRS recordings can therefore generally only be assumed to have correctly covered the targeted areas. Second, we have to consider some important potential drawbacks regarding the [O_2Hb] signals. Indeed, recent studies (e.g., Kirilina et al., 2012; Takahashi et al., 2011) have raised the question of the superficial (i.e., extra-cortical) contributions to NIRS signals measured at the scalp level. Among them, Kirilina et al. (2012) have notably evidenced that the superficial contributions are more pronounced in the [O_2Hb] and total hemoglobin signals, but not in the [HHb]. The authors suggested that looking at the changes [HHb] may allow identification of false positive in NIRS activation maps (i.e., erroneously attributing NIRS responses to cortical changes). In the present study, we found changes in both [O_2Hb] and [HHb] which brings some confidence as regards the attribution of the observed NIRS responses to cortical changes. Note that the Δ[HHb] changed significantly only above 40% of MVC for each cortical area investigated in this study. This can be explained by the existence of smaller changes in [HHb] compared to that in [O_2Hb] during neurovascular coupling — a phenomenon well “represented” by the balloon model (Buxton and Frank, 1997). Future investigations using methods to definitively separate cortical and extracortical signals in NIRS signals are warranted. These methods notably include the use of additional short source-detector separation optodes as regressors (Gagnon et al., 2012; Saager et al., 2011) and the analysis of the photon time-of-flight distribution in time-domain NIRS (Aletti et al., 2012).

Conclusion

In summary, our results indicate a bilateral activation over the SM1 and rostral PFC areas during a unilateral handgrip task for graded levels of force. In addition to this, the symmetry of the activation was demonstrated in all investigated levels of force concerning the SM1 areas, showing therefore that such a pattern is not limited to complex finger movements. We suggest that the visuo-guided control of force levels during a handgrip task requires cross-talk from ipsi- to contralateral SM1 to cope for the relative complexity of the task, similarly to that observed during complex sequential finger movement. We also proposed alternative ways to explain the symmetrical SM1 activation including (i) the ipsilateral CST and (ii) IHI mechanism. In addition, the more intense ipsilateral (right) rostral PFC activation compared to the contralateral (left) at the highest level of force reflects the higher attentional demand required to control the motor output. To better understand the symmetrical, or at least bilateral, cortical activation during unilateral handgrip tasks, the possibility of measuring inhibitory and excitatory inputs must be strongly considered.

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Graph-based transfer learning for managing brain signals variability in NIRS-based BCIs

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Abstract. One of the major limitations to the use of brain-computer interfaces (BCIs) based on near-infrared spectroscopy (NIRS) in realistic interaction settings is the long calibration time needed before every use in order to train a subject-specific classifier. One way to reduce this calibration time is to use data collected from other users or from previous recording sessions of the same user as a training set. However, brain signals are highly variable and using heterogeneous data to train a single classifier may dramatically deteriorate classification performance. This paper proposes a transfer learning framework in which we model brain signals variability in the feature space using a bipartite graph. The partitioning of this graph into sub-graphs allows creating homogeneous groups of NIRS data sharing similar spatial distributions of explanatory variables which will be used to train multiple prediction models that accurately transfer knowledge between data sets.

Keywords: Brain-computer interface (BCI), near-infrared spectroscopy (NIRS), brain signals variability, transfer learning, bipartite graph partitioning.

1 Introduction

A brain-computer interface (BCI) is a communication system that allows people suffering from severe neuromuscular disorders to interact with their environment without using peripheral nervous and muscular system, by directly monitoring electrical or hemodynamic activity of the brain [1]. Recently, near-infrared spectroscopy (NIRS) has been investigated for use in BCI applications [2]. NIRS-based BCIs employ near-infrared light to characterize alterations in cerebral metabolism during neural activation. During neural activation in a specific region of the brain, hemodynamic concentration changes in oxyhemoglobin (oxy-Hb) increase while those in deoxyhemoglobin (deoxy-Hb) decrease slightly [3] (see figure 1).

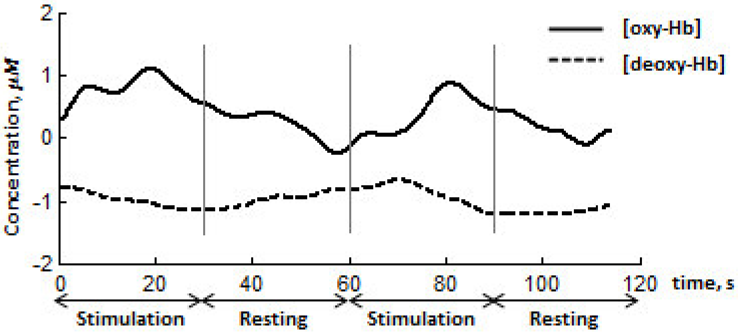

Fig. 1. Prototypical brain activity pattern using NIRS technology. Measured values of concentrations are relative and not absolute.

A BCI is considered as a pattern recognition system that classifies different brain activity patterns into different brain states according to their spatio-temporal characteristics [4]. The relevant signals that decode brain states may be hidden in highly noisy data or overlapped by signals from other brain states. Extracting such information is a very challenging issue. To do so, a long calibration time is needed before every use of the BCI in order to extract enough data used for feature selection and classifier training [5]. Because calibration is time-consuming and boring even for healthy users, several works in BCIs based on electroencephalography [1] addressed this problem by developing new data processing and pattern classification methods. [6] proposed a semi-supervised support vector machine (SVM) classifier designed to accurately classify brain signals with small training set. [7] used data recorded from the same subject during past recording sessions in order to determine prototypical spatial filters which have better generalization properties than session-specific filters. Other authors [5, 8-11] developed different subject-transfer frameworks to reduce calibration time before each use of a BCI. It consists of using data recorded from several users that performed the same experiment as a training set for a classifier that will be used to predict brain activity patterns of a new user. In NIRS-based BCIs, the problem of long calibration time has not been well addressed. Recent studies highlighted the need of changing data processing and classifiers design strategies in order to conceive more robust and practical BCIs [12-14]. To our best knowledge, [15] is the only work that addressed this issue by designing an adaptive classifier based on multiple-kernel SVM.

In this paper, we introduce a novel approach inspired from graph theory to address this problem. The novelty of our contribution compared to the works cited above lies in the fact of using a bipartite graph to have prior knowledge about variability in the feature space between brain signals recorded from different users. This prior knowledge allows designing a prediction model that adaptively chooses the best users set and features representation to accurately classify data of a new user and consequently reduce calibration time. The reminder of this paper is organized as follows. In section 2, we formalize the problem in the context of transfer learning between heterogeneous data. In section 3, we briefly review the background of bipartite graph partitioning and describe different steps of our approach. The effectiveness of our approach is demonstrated by an experimental evaluation on a real data set in section 4. Finally, section 5 concludes the paper and gives future directions of our work.

2 Problem formulation

Using traditional classification techniques for NIRS-based BCIs, the problem of classifying different brain activity patterns into different brain states can be stated as follows: given training data collected during the current recording session by performing several trials of different cognitive tasks, try to find a hypothesis h that allows good prediction of class labels corresponding to each cognitive task for the reminder of trials performed during the same session. Because classification performance of h increases with the size of training data, a long calibration time is necessary before each use of the BCI. In the context of transfer learning [16], the problem can be reformulated as follows. Given

1. A small amount of labeled NIRS signals recorded during the current session.
2. A large amount of labeled NIRS signals recorded during previous sessions of the same subject or from other subjects that performed the same experiment.

try to find a hypothesis h that allows good prediction of the class labels for the reminder of trials for the current session. Item 1 is called training set and item 2 is called support set. A single hypothesis h can achieve good classification performance when the training and support sets are assumed to be drawn from the same feature space and the same distribution. Such assumption may be too strong for our application because of high variability of NIRS signals collected from different subjects during different recording sessions which affects mostly the spatial distribution of explanatory variables (see figure 3).

In this paper, we design a prediction model which learns multiple hypotheses instead of one in order to overcome the problem of NIRS signals variability and accurately transfer knowledge between data of different individuals and different recording sessions. To do so, we divide our support set into multiple subsets $\{S_1, S_2, \ldots, S_K\}$ and we learn a hypothesis h_i for each subset S_i. The choice of the most appropriate hypothesis to predict class label y for a new trial x in the current session depends on the number of explanatory features shared between the training set T and each subset S_i. The general architecture of our approach can be expressed in a probabilistic manner as follows:

$$P(y/x) = \sum_{i=1}^{K} P(h_i/T)P(y/x, h_i) \tag{1}$$

In the next section, we illustrate how bipartite graph partitioning allows creation of multiple hypotheses which minimizes the influence of NIRS signals variability in the feature space on classification performance.

3 Transfer learning framework based on bipartite graph partitioning

In order to design a transfer learning framework for heterogeneous NIRS data, we model the spatial variability of explanatory features between different data sets. To do so, we propose to borrow the bipartite graph partitioning from graph theory [17-18]. This technique allows performing simultaneous grouping of instances and features and consequently mapping of data into richer space. This is important for reducing the effect spatial variability of brain signals on classification performance because each hypothesis h_i is drawn from explanatory variables in subset S_i.

3.1 Bipartite graph partitioning

Before describing different steps of our approach, we start with relevant terminology related to bipartite graph partitioning.
A bipartite graph $G = (D, F, E)$ is defined by two sets of vertices $D = \{d_1, d_2, \ldots, d_N\}$ and $F = \{f_1, f_2, \ldots, f_M\}$, and a set of edges $E = \{(d_i, f_j) / d_i \in D \text{ and } f_j \in F\}$. In this paper, we assume that an edge $E_{ij} = (d_i, f_j)$ exists if vertices d_i and f_j are related *(i.e.,* $E_{ij} \in \{0, 1\}$*).*

Assume that the set of vertices F is grouped into disjoint clusters $\{F_1, F_2, \ldots, F_K\}$. The set D can be clustered as follows: a vertex d_i $(i = 1 \ldots N)$ belongs to the cluster D_p $(p = 1 \ldots K)$ if its association with the cluster F_p is greater than its association with any other cluster in the vertex set F. This can be written as:

$$D_p = \{di \,/ \textstyle\sum_{j \in F_p} E_{ij} \geq \sum_{j \in F_l} E_{ij}, \forall\, l = 1, \ldots, K\} \tag{2}$$

Given disjoint clusters $D_1, \ldots, D_K$, the set of vertices F can be clustered similarly. As illustrated in [18], the optimal clustering of the two sets of vertices can be achieved when:

$$cut(D_1 \cup F_1, \ldots, D_K \cup F_K) = min_{V_1, \ldots, V_K} cut(V_1, \ldots, V_K) \tag{3}$$

where $V_1, \ldots, V_K$ is a K-partition of the bipartite graph (V_k, $k = 1, \ldots, K$ are sub-graphs of the graph G) and

$$cut(V_1, \ldots, V_K) = \textstyle\sum_{i<j} \sum_{p \in D(V_i), q \in F(V_j)} E_{pq} \tag{4}$$

It is well known that graph partitioning is a *NP*-complete problem. There are many heuristics that were introduced to give better global solutions and reduce complexity of bipartite graph partitioning. In this work, we use spectral clustering which is an effective heuristic that uses properties of graph Laplacian matrix to solve this problem. Because of space limitations, we will not show details of this heuristic. For more information, see [18].

3.2 Overview of our graph-based transfer learning framework

In our support set, the first set of vertices $D = \{d_1, d_2, ..., d_N\}$ corresponds to different data sets of NIRS signals recorded from different subjects during different sessions and the second set of vertices $F = \{f_1,f_2,...,f_M\}$ corresponds to M measurement channels placed on the same locations of participants' heads. A recording session consists of performing several trials of two cognitive tasks T_1 and T_2. Our approach is accomplished in three steps (figure 2).

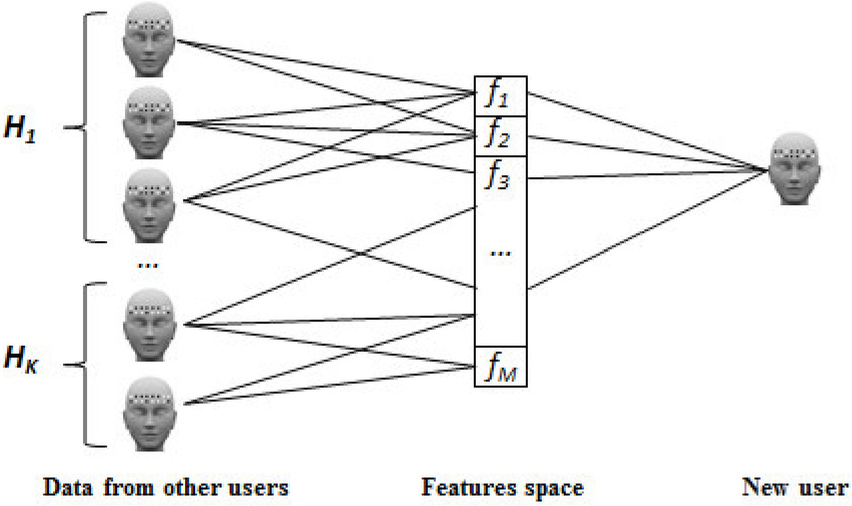

Fig. 2. Bipartite graph model for characterizing brain signals variability in the features space between different users.

Heterogeneous NIRS signals partitioning.

For each data set d_i, we perform features selection in order to find channels that allow detection of signals amplitude changes between different cognitive tasks. Then, we assign the number 1 to explanatory channels and 0 to the rest (*i.e.*, $E_{ij} \in \{0,1\}$). This channel selection procedure allows us to create an N by M co-occurrences matrix of data sets and channels and consequently create a representation of spatial variability of brain activity patterns in heterogeneous NIRS data. The creation of different groups of data sets $\{D_1, ..., D_K\}$ sharing similar spatial distributions of brain activity patterns $\{F_1, ..., F_K\}$ is performed by applying bipartite graph partitioning to the co-occurrences matrix.

Classifiers training.

After creation of several groups of NIRS signals having local features representations, a single classifier is trained on each group. The training performance of each classifier is evaluated using leave-one-out cross validation. The global performance of our prediction model is the average of all classifiers performance. If it is below the required performance, the bipartite graph partitioning step is repeated with different number of partitions.

New NIRS signals classification using the multiple-hypotheses prediction model.

Once prediction model training is finished, NIRS signals recorded during a new session will be classified as follows: first, we find the group of data sets sharing the most similar spatial distribution of brain activity patterns and then use the hypothesis trained on that data to predict class labels of each trial in the new session. In real time conditions, assuming that spatial distribution of brain activity patterns do not vary significantly during the same session, only the first few trials (*i.e.,* training set *T*) are used to find the closest co-cluster in our support set.

In the probabilistic interpretation of our transfer learning framework given in (1), $P(h_i/T)$ is calculated using "the winner takes all" rule and consequently $P(y/x)$ will be determined using only one hypothesis H_{i^*}:

$$P(h_i/\mathrm{T}) = \begin{cases} 1, \ if \ \sum_{j\in F_i} E_{Tj} \geq \sum_{j\in F_l} E_{Tj}, \forall\, l = 1, \dots, K \\ 0, \ otherwise \end{cases} \tag{5}$$

Then, $\exists!\, i^* \,/\, P(h_{i^*}/T) = 1$ and

$$P(y/x) = \sum_{i=1}^{K} P(h_i\,/T) P(y/x, h_i) = P(y/x, h_{i^*}) \tag{6}$$

4 Experimental Evaluation

In this section, our approach is evaluated on a real NIRS-based BCI data set using a linear discriminant analysis (LDA) classifier, which is the most widely used classifier in BCI applications [4], as a base learner. Then, its performance is compared to a single LDA classifier.

4.1 Data set description

To evaluate our approach, we used the publicly available data set described in [15]. It is composed of NIRS signals recorded from seven healthy subjects using 16 measurement channels. The study consisted of two experiments, each one lasted four sessions. The aim of the first experiment was to discern brain activation patterns related to imagery movement of right forearm from the activation patterns related to relaxed state, denoted respectively t_1 and b. While the aim of the second one was to discern brain activation patterns related to imagery movement of left forearm t_2 from the activation patterns related to relaxed state b. During each session, participants performed three trials of b and three trials of t_1 for experiment *1* and three trials of b and three trials of t_2 for experiment *2*. Thus, in each experiment, the first set of vertices D corresponds to *7* subjects × *4* sessions *(i.e.,* $D = \{d_1, d_2, \ldots d_{28}\}$*)*, while the second set of vertices corresponds to *16* channels *(i.e.,* $F = \{f_1, f_2, \ldots, f_{16}\}$*)*. Because the majority of NIRS-based BCIs studies reported that deoxy-Hb does not necessarily show significant changes in activated areas of the brain [3], we focused only on oxy-Hb changes.

4.2 Data preprocessing

NIRS signals going through human brain may be overlapped by many physiological (*e.g.,* respiration, heart beat) and experimental (*e.g.,* motion artifacts) sources of noise [3]. In order to minimize the effect of these sources of noise on classifiers performance, we applied a 5^{th}-oder Butterworth low-pass filter with cut-of frequency of *0.5* Hz. Another problem that we may encounter when we classify heterogeneous NIRS signals is the difference in amplitudes of hemodynamic brain activity between subjects, sessions or even trials performed during the same session [14]. To overcome this problem, we performed zero-mean and unit-variance normalization on time series data of each trial.

4.3 Results

In this study, we used the Wilcoxon rank sum test, which is a non-parametric statistical hypothesis test, to compare mean amplitude oxy-Hb time series averaged over time windows of imagery movement and relaxed state. Among *28* data sets in each experiment, *15* data sets in experiment *1* illustrated a significant difference in oxy-Hb amplitudes between time windows of imagery movement and relaxed state and *22* data sets in experiment *2*. Data sets in which no channel discerned activity patterns related to each brain state were removed resulting in *15* by *16* co-occurrences matrix for the first experiment and *22* by *16* co-occurrences matrix for the second one. Inter-subjects and inter-sessions variability in our data set are illustrated in figure 3.

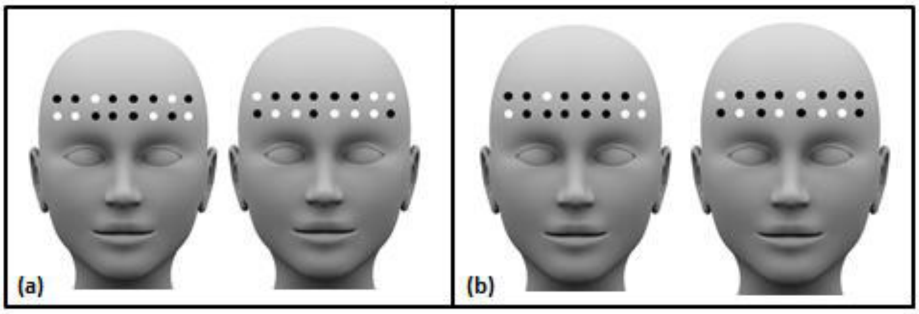

Fig. 3. Brain signals variability in NIRS-based BCIs. (a) Inter-sessions variability of explanatory channels for subject 5 in experiment 1. (b) Inter-subjects variability of explanatory channels for subjects 3 and 4 in experiment 2. White dots represent explanatory channels and black dots represent non-explanatory channels.

Because the number of trials in each session is not enough to evaluate our approach in online fashion, we tested it in a batch mode and compared classification results to a single LDA. As performance measurement, we used sensitivity and specificity which are respectively the probability that the activity pattern is classified as movement imagination given that the participant effectively performed movement imagination and the probability that the activity pattern is classified as relaxed state given that the participant was resting. The comparison results are illustrated in table 1.

Table 1. Comparison of classification performance of our approach and a single LDA classifier. The number of partitions is 2 in experiment 1 and 3 in experiment 2.

	Experiment 1		**Experiment 2**	
	Sensitivity	**Specificity**	**Sensitivity**	**Specificity**
LDA	0.60	0.71	0.65	0.68
Our approach	0.95	0.94	0.92	0.87

5 Conclusions and directions for future work

This paper proposed a graph-based transfer learning framework for accurately classifying heterogeneous NIRS signals recorded from different subjects during different sessions. It consists of modeling brain signals variability in the feature space using a bipartite graph and adaptively choosing the best users set and features representation used to train a classifier that will predict class labels of brain signals recorded during new session. The experimental evaluation of our approach compared to a single LDA classifier showed that our approach accurately transfers knowledge between different data sets despite the high variability of spatial distributions of explanatory channels between different users and different sessions of the same user.

Although first results are promising, many issues should be considered in future work. Boolean representation of the edges in our bipartite graph model may be not suitable for distinguishing robust features from non-robust ones. In fact, in NIRS-based BCIs there is a phenomenon of saturation which means that after performing several trials of different cognitive tasks the changes in oxy-hemoglobin and deoxy-hemoglobin concentrations between different brain states become non-significant in some regions of the brain [14]. Thus, features weighting may be important for designing robust classifiers which maintain good classification performance for long periods of time. Another important issue related to our transfer learning framework is the classifiers aggregation method given in (5). Choosing only one hypothesis may be non-suitable when the data set of current user shares many significant features with more than one partition in the support set. Other classifiers aggregation methods like weighted sum [19] and fuzzy integrals [20] will be investigated in future work.

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Résumé

Vers la discrimination des corrélats neuronaux des déficits d'attention: des Neurosciences Cognitives à l'Ingénierie Cognitive

L'attention focalisée est une fonction cognitive de haut niveau permettant à l'Homme de faciliter sélectivement certaines actions et perceptions. Dans un monde regorgeant de choix d'actions, et de possibilités de perceptions, l'attention focalisée représente une composante vitale de la cognition humaine. Un constat important doit cependant être noté : l'Homme est incapable de maintenir indéfiniment un état stable d'attention focalisée. Cette incapacité est mise en évidence pendant les tâches d'attention soutenue par l'apparition progressive de déficiences sensori-motrices au cours du temps. L'impulsivité motrice augmente alors, ainsi que le temps de réponse aux stimuli impératifs, et la sensibilité perceptive diminue. À l'heure actuelle, les bases neuronales du phénomène restent très peu connues et ce manque de connaissance est clairement perceptible au sein de deux champs disciplinaires - les Neurosciences Cognitives et l'Ingénierie Cognitive. En Neurosciences Cognitives, la question demeure ainsi posée : pourquoi l'Homme est-il incapable de maintenir un niveau de performance sensori-motrice optimal au cours de tâches d'attention soutenue ? En Ingénierie Cognitive, la problématique concerne le développement d'Interfaces Cerveau-Machine (ICM) passives : identifier les marqueurs neuronaux des déficits d'attention permettrait, à terme, de suivre en temps réel l'état cognitif de l'Homme et de l'alerter de la survenue de ces déficits durant son activité. Ces deux problématiques ont été traitées dans cette thèse.

Dans un premier temps, je démontre que le maintien d'une attention focalisée sur une stimulation visuelle entraîne une rapide inhibition des aires visuelles corticales. Cette inhibition sensorielle serait liée à l'absence de variation de la stimulation sensorielle. Ainsi, l'inhibition sensorielle serait bénéfique au cours de tâches de recherche visuelle : elle permettrait à l'Homme d'éviter de réexaminer plusieurs fois le même stimulus, le même objet, la même localisation spatiale ; mais lorsqu'une attention soutenue est requise, ce mécanisme serait alors à l'origine de l'apparition de déficiences sensorielles. La présence de cette inhibition sensorielle apporte une explication probante à la diminution de sensibilité perceptive et à l'allongement du temps de réaction qui caractérisent le phénomène. Je montre ensuite que l'activité de structures neuronales motrices et d'aires corticales connues pour sous-tendre l'attention focalisée (*i.e.*, tractus cortico-spinal, et aires corticales motrice primaire, préfrontale et pariétale droite) augmente progressivement au cours d'une tâche d'attention soutenue. Ce sur-engagement reflèterait un processus de compensation en réponse au désengagement préalable des aires corticales sensorielles et à la diminution de la qualité des représentations perceptives. Aussi, l'augmentation d'activité des structures neuronales motrices expliquerait l'augmentation de l'impulsivité motrice, une des signatures comportementales des déficits d'attention.

Dans un second temps, je teste la possibilité d'exploiter ces corrélats neuronaux des déficits d'attention afin de discriminer deux états attentionnels donnés (*i.e.*, avec ou sans déficits d'attention) au sein d'une ICM passive. Nous avons pour cela appliqué des méthodes de classification supervisées sur des données de spectroscopie proche infra-rouge reflétant l'activité hémodynamique des aires corticales préfrontale et pariétale enregistrées pendant une tâche d'attention soutenue. Nous rapportons des résultats encourageant en termes de performance de classification pour le futur développement d'ICM passives. Pris ensemble, les résultats décrits dans cette thèse apportent une meilleure compréhension des corrélats neuronaux des déficits d'attention et montrent comment cette connaissance peut être exploitée afin de développer des systèmes permettant de limiter la survenue d'accidents et d'incidents liés à l'erreur humaine dans un contexte écologique.

Mots-clés : attention soutenue, attention motrice, attention sensorielle, interfaces cerveau-machine passives, déficits d'attention.

Abstract

Disentangling the neural correlates of attention decrement: from Cognitive Neuroscience to Cognitive Engineering

Focused attention represents a high-level cognitive function enabling humans to selectively facilitate specific actions and perceptions. In a world full of choices of action, and of perceptual possibilities, focused attention appears to be a vital component of human cognition. One observation however, is worth making: human-beings are unable to maintain stable states of focused attention indefinitely. This inability manifests during sustained attention tasks with the progressive occurrence of sensory-motor deficiencies with time-on-task. The phenomenon - called attention decrement - is characterized by increases in motor impulsivity and in response times to imperative events, and by a reduction in perceptual sensitivity. So far, the neural underpinnings of attention decrement have not been fully elucidated and this lack of knowledge is clearly palpable within two disciplinary fields: Cognitive Neuroscience and Cognitive Engineering. In Cognitive Neuroscience, the associated question is why are human-beings unable to maintain an optimal sensory-motor performance during sustained attention tasks? In Cognitive Engineering, the lack of a complete scientific understanding of attentional issues impacts the development of efficient passive Brain-Computer interfaces (BCI), capable of detecting the occurrence of potentially dangerous attention decrements during the performance of everyday activities. Both issues have been addressed in this thesis.

In terms of Cognitive Neuroscience, I demonstrate that sustaining focused attention on a visual stimulation rapidly leads to an inhibition of the visual cortices. This sensory inhibition can be causally related to the lack of changes in perceptual stimulation typically characterizing sustained attention tasks. While the mechanism may be beneficial during visual search tasks as it helps humans avoid processing the same stimulus, the same object, the same location several times, it can lead to the occurrence of sensory deficiencies when sustained attention is required. As such, the sensory inhibition provides a compelling explanation as to the decrease in perceptual sensitivity and to the increase in reaction time that typify attention decrement. I show in a second study that attention decrement is associated with an increase in the activity of motor- and attention-related neural structures (*i.e.*, cortico-spinal tract, primary motor, prefrontal and right parietal cortices). This excessive engagement reflects a compensatory process occurring in response to the sensory disengagement already highlighted and to the related degradation of the quality of perceptual representations. It is notable that the excessive engagement of the motor neural structures with time-on-task provides a potential explanation for the increase in motor impulsivity typifying attention decrement.

In terms of application of these new findings, I investigated the potential of exploiting these neural correlates of attention decrement to discriminate between two different attentional states (*i.e.*, with or without attention decrement) through a passive BCI system. To do so, we applied supervised classification analyses on near-infrared spectroscopy signals reflecting the hemodynamic activity of prefrontal and parietal cortices as recorded during a sustained attention task. We achieved relatively promising classification performance results which bode well for the future development of passive BCI. When considered together, the results described in this thesis contribute towards a better understanding of the neural correlates of attention decrement and demonstrate how this novel knowledge can be exploited for the future development of systems which may enable a reduction in accidents and human error-driven incidents in real world environments.

Key-words: sustained attention, motor attention, sensory attention, passive brain-computer interfaces, attention decrement.