The National University of Ireland Maynooth

Falling Head Over Heels: Investigating the higher-level cognitive and electrophysiological processes underlying gait control and falls in older adults and stroke survivors.

Thesis submitted to the Department of Psychology, Faculty of Science and Engineering, in fulfilment of the requirements for the degree of Doctor of Philosophy, National University of Ireland Maynooth.

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October 2016

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Acknowledgements

Overall, I feel incredibly privileged to have had this opportunity to learn and I couldn't have done it without the love and support from a large number of wonderful people for whom I am incredibly grateful.

I consider myself very lucky to have been supervised by the dynamic duo of Dr Seán Commins and Dr Richard Roche. You both inspired my interest in cognition and neuroscience from the undergraduate degree, and have shaped me, since then, into the researcher I am today. You have both been incredibly kind, patient, encouraging, and supportive over the past 5 years. I have learned so much from you, thank you.

I owe so much to my family also for their support throughout. I'm not sure they fully understood why I wanted to do this PhD, nor exactly what it was that I was doing out here in Maynooth day-to-day, but they supported me all the way. Mam, Dad, Eileen, and Ed: I love you, thank you.

To all those friends throughout the years who helped me out, I have so much gratitude. A special thank you must go to those at the end who put up with my bizarre behaviour in the final writing stage. So many thanks to my dear friends Louis and Seán who kept me on the straight and n-*arrow*. Louis, thank you for being a perfect all-rounder, offering distraction, support, motivation and comic relief on a daily basis! Equally, to Seán, who put up with my crazy at work and at home, and who was always there to help (with words or with wine) when I needed it (#Shliz2k16). Thanks to my prodigal friend Maireád who was there at the start and again in the end, you were so vital in the last few weeks (from yoga, to pints–and Darren too, thanks). Thanks as well to Marion who has been there through it all, and to Ciara and Colin who have been great friends here and there (Ghent) over the years. Thanks to Noeleen and Joe who were mentors at first and friends throughout, with lots of valuable supports along the way. Also many thanks to Kate for your kindness, positivity and cakes! To Jules, Baz, Tyler, Matt and my roomies Anna, Caroline, and Clare: thanks for putting up with me and for the support and encouragement. You all believed in me in one way or another, and were there when I needed relief.

Thanks also to all the staff in the Department of Psychology at Maynooth University for being so friendly and supportive, with special thanks to Anne, Victoria, Caroline, and Derek for always being ready to help.

I also want to acknowledge and thank Dr Rónán Collins at Tallaght hospital for his collaboration and support, and Dr Matt Patterson for his collaboration (and friendship thereafter). Many thanks also to all the participants who took an interest in this work and who so kindly volunteered their time.

To everyone who has known me over the past 5 years, those named here, and those without: thank you, thank you.

Publications and Presentations Arising from this Thesis

Walshe, E. A., Patterson, M. R., Commins, S. & Roche, R. A. (2015). *Dual-task and electrophysiological markers of executive cognitive processing in older adult gait and fall-risk.* Frontiers in Human Neuroscience, 17 (9):200. doi: 10.3389/fnhum.2015.00200

Walshe E. A., Commins S, Patterson M and Roche RA (2014). *Falling Head Over Heels: Investigating the higher-cognitive and electrophysiological processes underlying gait and falls.* Front. Neurosci. Conference Abstract: Neuroscience Ireland Young Neuroscientists Symposium 2014 . doi: 10.3389/conf.fnins.2014.87.00008

Walshe, E., Commins, S. & Roche, R. A. P. (2014). *Falling Head Over Heels: Assessing the cognitive and electrophysiological processes underlying gait and falls*. Proceedings of the ISPGR World Congress, Vancouver, Canada.

Walshe, E., Roche, R. A. P. & Commins, S. (2013). *Falling: Head Over Heels. The cognitive and electrophysiological correlates of walking gait and fall-risk.* Proceedings of the 8th Neuroscience Ireland Conference. Cork, Ireland.

Walshe, E., Hagerty, A., Roche, R. A. P. & Commins, S. (2012). *The role of executive functioning in spatial navigation: Effects of visuo-spatial, motor and vestibular dual-tasks on gait parameters.* FENS Forum Abstr. 2012, 2189, Volume 6, p158.3.

Walshe, E., Commins, S. & Roche, R. A. P. (2013). *Investigating the cognitive and electrophysiological correlates of gait in young and older adults.* The 2nd Joint World Congress of the International Society for Posture and Gait Research, and Gait & Mental Function. Akita, Japan (June, 2013). [Poster]

Abstract

Falls are a common problem for Ireland's older adults and stroke survivors, which have severe consequences for the individual and high care costs for the state. Current clinical interventions that focus solely on musculoskeletal function are not evidenced to be consistently effective in the long term, or in those older adults without muscle and bone impairments (Cadore, Rodríguez-Mañas, Sinclair, & Izquierdo, 2013; Teasell, McRae, Foley, & Bhardwaj, 2002). The role of cognition in gait control and falls has become increasingly apparent, with higher-level executive functions exhibiting a clear relationship with falls and cognitive decline with ageing (Morris, Lord, Bunce, Burn, & Rochester, 2016). This research aims to address a gap in the literature by identifying the specific higher-level executive processes that play a role in gait control, and examining if these processes are impaired in older adults and stroke survivors with a high risk of falling. Behavioural and electrophysiological measures were used to examine walking gait in both single- and dual-task conditions, as well as cognitive performances and the associated event-related potentials in healthy young and older adult "fallers" and "non-fallers", and also in a sample of stroke survivors. The results suggest that executive top-down processes (working memory in particular), play a role in gait control during dual-task walking generally, and that executive processes are relied upon more in older age. This work suggests that there may also be neural markers of "successful" ageing that differentiate fallers from non-fallers, and that there can be substantial recovery of both cognition and gait post-stroke. These findings support the resource capacity and compensatory theories of neurocognitive ageing, and suggest that executive neuropsychological tasks could be developed to offer alternative cognitive/neural fall screening assessments and rehabilitation programmes for stroke patients and the wider older adult population.

Chapter 1

General Introduction

The vertical bipedal locomotion of primates–likened to a highly unstable inverted anatomical pendulum–is a remarkable feat, and unparalleled in any other species. Along with the large expansion of the frontal cortex (namely the inferior frontal gyrus), this unique and highly energy efficient upright gait distinguishes us from apes, and has been attributed, by some, to a supposed evolutionary shift in postural control to higher levels of the central nervous system and the cerebral cortex (Niemitz, 2010; Skoyles, 2006; Wang, Uhrig, Jarraya, & Dehaene, 2015). The ability to remain upright with dynamic postural control while walking is a complex operation necessary for everyday functioning, and requires the integration of information from multiple sensory, motor and cognitive systems. Furthermore, as humans, we display a remarkable ability to navigate while multitasking in everyday life. We walk and think, walk and talk, and walk and text. We walk with the dog, while carrying toddlers, and balancing groceries. We plan trajectories up and down slopes and steps, and navigate around moving and stationary obstacles, both human and object. Sometimes we do all of this with apparent automaticity. Sometimes, however, we trip, we stumble, we fall.

1.1. The Problem of Falls

Falls are a global healthcare problem for older adults, with both national and international reports estimating that one third of adults over the age of 65, and half of those over the age of 80, experience at least one fall each year (Health Service Executive, 2008; World Health Organisation (WHO), 2007). Falls account for 40% of all injurious deaths (WHO, 2007) and are a leading cause of injury-related hospital admission over the age of 65, accounting for 44.1% in an Irish population study in 1995 (Laffoy, Igoe, & O'Herlihy, 1995). Falls also commonly lead to a number of negative outcomes for the individual, namely: functional decline (in terms of activities of daily living), physical

injury/disability (e.g. hip fracture), negative sociological and psychological consequences (fear of falling leads to less activities outside of the home), loss of living independence with subsequent admittance to nursing home care, and even death (Rittman, Boylstein, Hinojosa, Sberna Hinojosa, & Haun, 2007; Rubenstein, 2006; Vellas, Wayne, Romero, Baumgartner, & Garry, 1997).

Falls are also a particular problem for older adults who have experienced a stroke, with higher incidence rates than community-dwelling older-adults making stroke survivors a high fall-risk group of the population (Batchelor, Mackintosh, Said, & Hill, 2012; Jorgensen & Jacobsen, 2002; Simpson, Miller, & Eng, 2011). Approximately 23-62% of survivors experience at least one fall post-stroke (Langhorne et al., 2000; Lim, Jung, Kim, & Paik, 2012), with some studies reporting that up to 73% of people fall after rehabilitation (6+ months post stroke: Forster & Young, 1995; Mackintosh, Goldie, & Hill, 2005). Falls also occur most often whilst walking in stroke survivors (Hyndman, Ashburn, & Stack, 2002). One Dublin-based study reported that 23.5% of stroke patients experienced at least one fall at a 2-year follow up, with 14.2% of the sample reporting more than one fall post-stroke (Callaly et al., 2015). In addition to the negative outcomes of falls outlined above, falls following a stroke also come with drastic setbacks in cognitive and motor recovery or further disability, including longer hospital stays of up to 11 days (Teasell, McRae, Foley, & Bhardwaj, 2002; Wong, Brooks, Inness, & Mansfield, 2016). Falls post-stroke also have particularly high morbidity and mortality rate (Divani, Vazquez, Barrett, Asadollahi, & Luft, 2009; Langhorne et al., 2000). The functional recovery goals of stroke survivors, particularly the ability to carry out activities of daily living, makes recovery of gait post-stroke a priority (Belda-Lois et al., 2011).

In addition to the personal suffering of the individual, falls and their negative outcomes also place a severe strain on healthcare services, at a considerable cost to the

state. In 2007, the estimated total cost of older adult falls and fractures in Ireland was €402 million, a figure which was estimated to be in excess of €500 million by 2010 (Gannon, O'Shea & Hudson, 2007). Annual stroke care is now estimated to exceed €1 billion (4% of total health care expenditure), of which 40% accounts for nursing home facility costs for dependent patients, with an estimated in-patient cost of €59 million for fall-related injuries in elderly adults (Irish Heart Foundation (IHF), 2010; HSE, 2008). The prevalence rates of stroke, and of falls in older adults, are only expected to increase with Ireland's ageing population demographic in years to come (with a 50% increase in stroke patients by 2021–IHF, 2010; HSE, 2008). Although Ireland's population is young in comparison to other European countries, the percentage of older adults is increasing. In a 2014 report, the number of adults over the age of 85 in Ireland was predicted to double by 2025 (National Social Monitor 2014). Therefore, the burden of falls due to ageing, stroke and other age-related illnesses is a growing healthcare problem. This problem needs to be addressed with improved intervention and rehabilitation protocols that aim to understand the complexity of gait and restore functional independence, rather than merely offer compensation.

1.1.1. Fall assessment

Falls are defined as "a sudden, unintentional change in position causing an individual to land at a lower level, on an object, the floor, or the ground, other than as a consequence of sudden onset of paralysis, epileptic seizure, or overwhelming external force" (Feder, Cryer, Donovan, & Carter, 2000, p. 1007). Clinically, traditional subjective and semi-subjective qualitative medical assessments of gait performance have been used to predict fall-risk (Muro-de-la-Herran, García-Zapirain, Méndez-Zorrilla, Garcia-zapirain, & Mendez-zorrilla, 2014). Clinicians visually inspect a patient's gait by observing their

walk over a short distance, and consider this in light of the patient history and physical examination (Levine, Richards, & Whittle, 2012; Sigman & Dehaene, 2006). Sometimes speed may be recorded with a stopwatch, or a video recording of the patient's gait would be taken for further qualitative inspection (Levine et al., 2012). Semi-subjective assessments of functional gait and balance performance include the commonly used Dynamic Gait Index, Timed up and Go test, and Berg Balance Scale (Hayes & Johnson, 2003). These performance-based assessments are used to identify functional limitations, however research has also shown that these tests fail to predict falls in community older adults who are active and independent: i.e. idiopathic fallers (Boulgarides, McGinty, Willett, & Barnes, 2003). The subjective nature of these assessments leaves them open to human error and inaccuracy, which has negative implications for diagnosis and rehabilitation (Sigman & Dehaene, 2006), as they lack validity, reliability, sensitivity, and specificity (Krebs, Edelstein, & Fishman, 1985; Saleh & Murdoch, 1985; Toro, Nester, & Farren, 2003).

However, recent technological advancements now allow for more objective quantitative analysis, offering more precise measurement of general spatial and temporal parameters of gait: e.g. speed, stride time, stride length (Levine et al., 2012; Sigman & Dehaene, 2006). These technologies include a broad range of devices and systems such as footswitches, accelerometer and gyroscope sensors, instrumented walkways, force platforms, and camera-based motion capture systems (Levine et al., 2012). Optical motion systems remain the gold standard of 3D gait analysis (Agostini, Antenucci, Lisco, & Gastaldi, 2015; Muro-de-la-Herran et al., 2014). However, many of these systems are not accessible or practical in a clinical setting for quick assessment of a patient's gait (Levine et al., 2012). Recent developments in wearable gait analysis systems now provide cost-effective wireless accelerometer and gyroscope sensors that are discrete, portable,

quick and easy to use. These are comparable to other qualitative and quantitative measures in estimates of gait parameters, and may provide an opportunity for quantitative gait assessments in the clinic setting in the near future (Agostini et al., 2015; Sant'Anna, Wickström, Zügner, & Tranberg, 2012).

Many studies have examined the specific spatial and temporal gait parameter impairments that predict fall risk in both older adults and post-stroke (Verghese, Holtzer, Lipton, & Wang, 2009). The gait cycle is most often analysed with respect to the heel and toe events (heel-strike and toe-off), which can be used to determine spatial and temporal parameters of locomotion (Levine et al., 2012). The most commonly reported characteristic is gait speed, however there are a number of other gait parameters that are independently associated with fall risk: these include cadence, stride time, stride length and variability measures (Taylor, Delbaere, Mikolaizak, Lord, & Close, 2013; Verghese et al., 2009). Gait speed is calculated as the distance walked in the time taken, and cadence as the number of steps per minute. Stride time–often referred to as a single gait cycle–is calculated as the time between successive heel-strikes of the same foot. The distance covered during a stride is the stride length. Stride time variability and stride length variability are also used as parameters of gait for analysis. Variability is calculated as the coefficient of variation (CV) of stride time and length, which is the percentage of the standard deviation (SD) divided by the mean of all gait trials or cycles (Hausdorff, Rios, & Edelberg, 2001). This is a common linear measure of variability that represents the magnitude of temporal variations (Lord et al., 2013). However, there are also non-linear measures such as maximum Lyapunov exponent and entropy that describe the organisation of the temporal variations (Vieira et al., 2017). Other measures include: swing time and stance time (calculated as the time the foot is and is not in contact with the floor, respectively–toe-off to heel-strike, and heel-strike to toe-off), swing/stance ratio

(ratio of time between swing and stance) and asymmetry values of time between left and right leg gait events (Levine et al., 2012)–see Chapter 2, section 2.4.2 for more details.

Community-dwelling healthy older adults walk slower, with shorter strides, and have an increased stride time variability compared to younger adults, when walking at a comfortable walking pace (Taylor et al., 2013). However, these age-related changes in gait do not necessarily indicate high fall-risk, and may be compensatory to maintain balance in the face of declining sensory and motor functioning with age. Normative values of gait speed in a nationally representative sample from Ireland show that gait speed slows linearly from the age of 50 to 85 years (Kenny et al., 2013). Fall risk and cognitive decline in older adults are predicted by slower speeds (Abellan Van Kan et al., 2009; Holtzer et al., 2007; Mielke et al., 2013; Ostir et al., 2015; Verghese et al., 2009), and gait variability has been proposed as a sensitive measure of instability that is indicative of fall-risk and future cognitive status (Gomes et al., 2016; Hausdorff et al., 2001; Lord, Howe, Greenland, Simpson, & Rochester, 2011; Verghese et al., 2009). Older adults with cognitive impairment also exhibit shorter steps, slower speed, and greater variability–that is predictive of fall-risk–than cognitively intact older adults (Maquet et al., 2010; Taylor et al., 2013).

More recently, researchers have established distinctive domains of gait consisting of different temporal and spatial gait characteristics that group together when factor analysis is applied. These domains have been differentially associated with fall-risk and cognitive impairment in older adults (Creagh et al., 2016; Verghese et al., 2008). Initially, three domains of **pace**, **rhythm** and **variability** were identified (Verghese, Wang, Lipton, Holtzer, & Xue, 2007b). However, more recent work has added a domain of **asymmetry** and **postural control**, resulting in five domains of gait (J. Hollman & McDade, 2011; Lord et al., 2013). See Table 1.1. for the five domains and their clusters of gait parameters

according to Lord et al. The domains of rhythm and variability have previously been associated with fall risk in older adults (Verghese, Holtzer, Lipton, & Wang, 2009), and the pace domain has been associated with attention and executive functioning (Inzitari et al., 2007; Lord et al., 2011). Executive functions are involved in the temporary maintenance and manipulation of sensory information, and goal-oriented planning (McCabe, D, & Hambrick, 2010).

Table 1.1 *Five factor domains of gait and their clusters of individual gait characteristics, as identified by Lord et al. (2013) and Hollman and McDade (2011).*

Domain	Spatiotemporal Gait Characteristic
Pace	Speed (m/s) Step length (m) Step time variability (ms %) Step swing time variability (ms %) Step stance time variability (ms %)
Rhythm	Step time (ms) Step swing time (ms) Step stance time (ms)
Variability	Step velocity (m/s %) Step length variability (m %) Step width variability (m %)
Asymmetry	Step time asymmetry (ms) Step swing asymmetry (ms) Step stance asymmetry (ms)
Postural Control	Step width (m) Step length asymmetry (m)

1.1.2 Risk factors

While gait impairments are one of the most important risk factors for falls in both older adults and stroke survivors (Campbell, Borrie, & Spears, 1989; Hausdorff et al., 2001; Weerdesteyn, de Niet, van Duijnhoven, & Geurts, 2008), it is important to understand other predictive factors in order to develop targeted screening and prevention strategies. Varying extrinsic/environmental factors and intrinsic individual/personal factors have been identified for fall-risk. Extrinsic factors include medications/polypharmacy, inappropriate (ill-fitting) footwear, and environmental tripping hazards such as loose carpet/rugs or slippery floors, unstable furniture and poor lighting (Ambrose, Paul, & Hausdorff, 2013; HSE, 2008; Pasquetti, Apicella, & Mangone, 2014). Intrinsic risk factors include advancing age, female gender, gait impairments, history of falls, fear of falling, musculoskeletal impairments (lower limb muscle weakness, arthritis), sensory deficits, disease symptoms, declining functional abilities and cognitive impairment (Ambrose et al., 2013; HSE, 2008). Of these, previous falls, gait and balance impairments, polypharmacy, age, female gender, environmental factors and cognitive impairments (particularly attention and executive function impairments) appear to be the most common risk-factors (Ambrose et al., 2013). Thus, in the following studies we attempted to counterbalance the sex of participants and asked in the telephone screening process about any medications participants were taking, particularly those stating side effects of dizziness or balance impairments, in an attempt to minimise the effects of polypharmacy on our findings. Individuals who were taking numerous medications were often excluded due to other health issues that met the criteria for exclusion.

1.1.3 Prevention and intervention

Current fall prevention strategies are targeted towards the above risk factors. Unfortunately, many of these risk factors are unmodifiable (such as previous history of a fall, gender, age, etc), and cannot be used as targets for modification in falls rehabilitation. Thus, current multi-factorial assessments and interventions investigate the various modifiable causes of falls and aim to reduce future risk by means of medical treatment, training muscles and balance, and modifications in the home to reduce hazards (Segev-Jacubovski et al., 2011). However, the role of cognition has been largely overlooked. Traditionally, walking was considered an automated biomechanical and reflexive motor function, with some voluntary control, but primarily relying on central pattern generators located at the spinal cord, brainstem and cerebellum (Clark, 2015; Guertin, 2013; Jahn et al., 2008). Concomitantly, falls in older adults were largely considered a result of age-related declines in sensory and musculoskeletal function (e.g. muscle weakness, arthritis, osteoporosis, visual impairment). Unfortunately, many of the ensuing musculoskeletal interventions (e.g.: strength training, gait re-training, body-weight support, EMG biofeedback and splinting of the lower extremity) are not consistently effective in the long term (Cadore, Rodríguez-Mañas, Sinclair, & Izquierdo, 2013; Teasell, McRae, Foley, & Bhardwaj, 2002). Furthermore, multifactorial interventions also reveal no effects or only limited effects on reducing fall risk in older adults with and without cognitive impairment (Michael et al., 2010; Shaw et al., 2003). Furthermore, many of these interventions are not applicable to idiopathic older fallers without physiological impairments or neurological diagnosis (Buchner et al., 1997; Schlicht, Camaione, & Owen, 2001).

We know that in addition to sensory and motor decline, cognitive function also declines naturally with ageing (Deary et al., 2009; Park, 2000; T. A. Salthouse, 2009b). Yet cognition has only recently been recognised as a modifiable risk factor for falls (Muir,

Gopaul, & Montero Odasso, 2012; Rubenstein, 2006). Thus, the traditional clinical interventions outlined above largely neglected cognitive aspects of gait and locomotion, failing to specifically focus on incorporating cognition into physical therapy. However, recent research in Parkinsonian rats shows that skill-based exercise requires more cortical processing, motor control and flexibility than non-skilled aerobic training with new Parkinson's disease (PD) interventions focusing on dual cognitive and motor exercise for improving quality of life (Jakowec, Wang, Holschneider, Beeler & Petzinger, 2016).

1.2 The Cognitive-Motor Link

Evidence of a cognitive-motor link comes from recent cross-sectional studies identifying associations between falls, gait and cognition in normal ageing and neurodegenerative disorders such as mild cognitive impairment, dementia and Parkinson's disease (Demnitz et al., 2016; Morris, Lord, Bunce, Burn, & Rochester, 2016; Muir et al., 2012). Furthermore, longitudinal studies have also evidenced gait as a predictor of cognitive decline (Verghese et al., 2014). Fall incidence appears to progressively increase with cognitive impairment in older adults, with 60% of cognitively impaired older adults falling each year, and up to 80% of persons with dementia, which is twice that of cognitively-intact older adults (Laird, Studenski, Perera, & Wallace, 2001; Shaw et al., 2003). Data from over five thousand individuals in the Irish Longitudinal Study on Ageing (TILDA) have also revealed that mild cognitive impairment (defined by global clinical measures) is retrospectively associated with higher incidence of falls in older adults over the previous 12 months (Tyrovolas, Koyanagi, Lara, Ivan Santini, & Haro, 2015).

A systematic review by Muir et al. in 2012 found that global cognitive impairment (and executive domain impairment) was associated with falls and fall injuries in older

adults. The inverse relationship between cognition and disability in older adults also seems to be mediated by habitual gait speed (Kuo, Levelle, Yu, & Millberg, 2007), and gait speed also independently predicted onset of cognitive impairment better than other measures of physical performance over a 4.4 year follow-up (Veronese et al., 2016). The mediating role of habitual gait speed in Kuo et al.'s study could indicate a mid-brain dysfunction affecting gait, and requiring more cognitive input, as in the case of sub-clinical Parkinson's disease. However, this would only apply to habitual gait speed (and not goal-directed speed). More recent systematic reviews and meta-analysis studies have found positive associations between gait speed and other mobility measures, and different cognitive domain performances (Demnitz et al., 2016; Morris et al., 2016). Demnitz et al. (2016) conducted a review and meta-analysis of mobility and cognition in older adults and found that gait and lower extremity function (and to a lesser extent, balance) were positively correlated with cognition. Namely, slower speed was associated with worse global cognition (mainly on the Mini Mental State Examination: MMSE) and executive function scores, with smaller effects for an association between gait speed and memory, and speed of processing. Demnitz et al. concluded that there is a global association between mobility and cognition in older adults, but not all cognitive processes (e.g.: visuospatial, working memory processes), nor all aspects of gait (e.g.: stride time, stride length, gait variability) were included in the reviewed literature.

Another recent structured review by Morris et al. (2016) also analysed the association between gait and cognitive performances in older adults with and without cognitive impairment and Parkinson's disease. However, this review attempted to focus on the discrete relationship between independent gait and cognitive domains, given that the commonly reported gait speed is a global gait metric and arguably cannot represent the subtle changes in ageing and pathological gait. Using the gait domain classification

system proposed by Lord et al. (2013: see Table 1.1above), Morris et al. found that the pace domain of gait was most commonly studied in all three samples and predicted cognitive decline. In older adults, pace was strongly associated with attention and executive functions, and somewhat with processing speed, language and visuospatial processing, but not global cognition. The same relationship between pace and attention and executive function was evident, albeit less strongly, in the cognitive impaired samples (AD, frontotemporal dementia and mild cognitive impairment). For all other gait domains, many samples had no associations with various cognitive domains, or the literature had inconsistent or contradictory evidence of associations, resulting in no clear trends. Morris et al. also attempted to map the underlying pathological neural mechanisms of the gait and cognitive associations, and found that some of these common substrates differed across age and pathology (see Figure 1.1 below). However, the model does not include measures of asymmetry and postural control, and is dominated by links to speed and pace. Therefore, this model is arguably too general to guide interpretation of the current research as it stands. These findings by Morris et al. call for future studies to examine associations between more comprehensive batteries of cognition and gait. This will lead to a more specific understanding of the selective rather than global relationship between aspects of gait and cognition, and aid in the development of more specific screening and rehabilitation protocols.

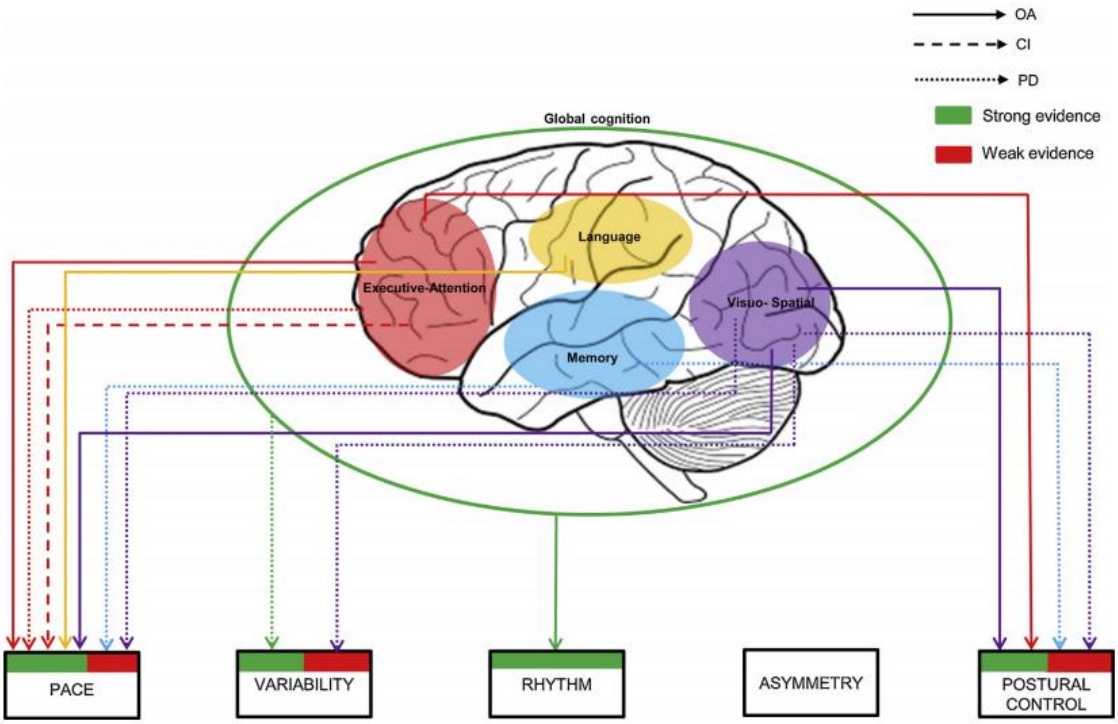

Figure 1.1 *A map of associations between domains of gait and cognition, and the underlying neural mechanisms in older adults (OA: solid line), CI (cognitive impairment: dashed line) and PD (Parkinson's disease: dotted line), as proposed by Morris et al., 2016. Permission for reuse obtained from Elsevier on 17/10/2016.*

Morris et al. also reviewed more recent longitudinal studies that have allowed for investigation of the direction of the relationship between gait and cognition in older adults. Previously, cognitive impairment and dementia have been counted as risk factors for falls (Skelton & Todd, 2004; Van Doorn et al., 2003), with global cognition, executive function and memory predicting decline in pace domain parameters–primarily gait speed (Morris et al., 2016). However, it has also recently become apparent that gait measures can longitudinally predict cognitive decline and diagnosis of dementia, with gait speed shown to predict cognitive decline in ageing adults (Mielke et al., 2013). Morris et al. also highlight that multiple studies of community older adults reveal the pace domain as a strong predictor of global cognition (Auyeung et al., 2011; Dodge et al., 2012; Taniguchi et al., 2012), with fewer studies showing pace predicts executive function decline and processing speed (Inzitari et al., 2007; Verghese et al., 2008).

Work by Verghese et al. has shown that the pace and rhythm domains predict memory decline and dementia onset, with only the pace domain predicting executive function decline (Verghese et al., 2007b). Verghese et al. have thus proposed a Motor-Cognitive Risk (MCR) syndrome as a prodome syndrome for dementia diagnosis that is characterised by slow gait and cognitive complaints (Verghese, Wang, Lipton, & Holtzer, 2013). MCR has been evidenced to commonly occur in older adult populations across multiple countries (Verghese et al., 2014), and is associated with increased mortality (Ayers & Verghese, 2016). Recent work using the TILDA national data set in Ireland (Maguire et al., 2016) reveals prevalence rates of 2.3% which are lower than the previously reported 7% prevalence by Ayers and Verghese (2016). Furthermore, gait and balance measures have been evidenced as predictive markers of cognitive decline in stroke survivors up to 2 years post-stroke event (Ben Assayag et al., 2015). This finding comes from the Tel Aviv Brain Acute Stroke Cohort study–a large prospective cohort study–in which they found that development of cognitive decline after 6 months was associated with longer performances on the Timed Up and Go test, lower Berg Balance Scale scores, slower gait, and poorer dual-task accuracy while walking.

1.4 Theoretical accounts of the cognitive-motor link

The mounting evidence above supporting the relationship between cognition, gait and falls has challenged the long held belief that gait impairments and falls in older adults are solely attributable to sensorimotor decline. Traditionally, walking gait has been considered an automated biomechanical process, whereby age-related slowed motor responding and declines in musculoskeletal, visual, vestibular and proprioceptive functioning were considered responsible for increased falls in older adults (Segev-Jacubovski et al., 2011). Studies of postural control during quiet standing have shown

that older adults are less stable overall than younger adults, and are particularly unstable when visual and proprioceptive inputs are altered or unavailable (Teasdale & Simoneau, 2001). Studies of ageing gait have also revealed that declining sensorimotor functions are a factor in gait decline in older adults (Callisaya et al., 2009; Xie, Liu, Anson, & Agrawal, 9000). Neuroimaging studies of the ageing brain and motor control have suggested that motor cortical and corpus callosum atrophy is associated with slower movements and poorer coordination, as well as postural balance and gait impairments (Seidler et al., 2010; Tang & Woollacott MH., 1996).

Older adults also show more widespread brain region activity for the performance of motor tasks (including the prefrontal cortex) in comparison to younger adults, suggesting that the motor network is adaptive to maintain performance in the face of age-related degeneration (Ward & Frackowiak, 2003). Furthermore, the case for a stronger cognitive-motor link with ageing is evident in positive correlations between frontal region activation and motor performances in older adults (Heuninckx, Wenderoth, & Swinnen, 2008; Seidler et al., 2010). In parallel, neuroimaging studies of cognitive control have shown similar differential patterns of brain activity in young and older adults, and a number of models and theories have been proposed in the field of cognitive neuroscience to explain these age-related changes. Examination of these theories may offer some insights into the neural mechanisms underlying the relationship between gait, falls and cognition in normal ageing adults and those with cognitive impairment.

1.4.1 Theories of cognitive ageing

Numerous studies have highlighted that age-related declines in cognitive function capabilities are not ubiquitous. There can be simultaneous declines in some cognitive abilities (fluid cognition), while older adults can also maintain performance, or have

superior performance in other forms of cognitive capacities (crystallized abilities: learned skills and knowledge): for example, older adults have more extensive vocabularies and world knowledge capacity (Cattell, 1963; Harada, Love, & Triebel, 2013; T. A. Salthouse, 2009a). However, age-related declines are consistently observed for fluid cognitive functions such as memory, executive control (sustained attention, attention regulation and decision making), and processing speed after the third decade of life (Glisky, 2007; Harada et al., 2013; T. Salthouse, 2012). These functions underlie the ability to process and learn new information, solve problems and allocate attention to the environment, all of which can be arguably considered important when walking around obstacles and navigating an environment. Park (1999) highlights a parallel distinction between controlled effortful processing that exhibits age-related declines, and automatic processing that remains intact. In light of this, the above evidence of declines in motor control of locomotion (instability and falls) in older adults may indicate that walking gait is an effortful task, influenced by age-related cognitive declines.

A number of cognitive ageing theories attempt to explain some anomalous ageing research findings, such as: why only some older adults exhibit declining cognitive performance while others appear to maintain performance; why there is differential brain activation in young and older adults, and why there can be increased activation in brain areas that have been associated with age-related behavioural performance declines (Cabeza, Anderson, Locantore, & McIntosh, 2002). The **cognitive reserve theory** posits that a number of factors such as high levels of education, physical activity and mental activity may mediate clinical manifestations of cognitive decline due to age-related neuropathology (Meng & D'Arcy, 2012; Stern, 2002). This comes from epidemiological evidence that not all older adults exhibit the clinical symptoms of cognitive decline (such as cognitive impairment and symptoms of dementia), yet evidence of the neural basis of

this reserve is still elusive (Steffener & Stern, 2012). This cognitive reserve (akin to brain reserve capacity) theory suggests that some older adults can maintain functional abilities despite declining neural pathology, due to an ability to adapt and flexibly optimise or maximise neural networks, or to recruit additional networks (Jellinger & Attems, 2013; Stern, 2002; Whalley, Deary, Appleton, & Starr, 2004).

Two key hypotheses have been proposed to explain neurocognitive ageing which underpin a theory of cognitive reserve: one of **neural compensation** and one of **neural dedifferentiation**. The dedifferentiation hypothesis proposes that the ageing process results in widespread less distinctive and less efficient neural recruitment, which can result in poorer task performances in general (Cabeza et al., 2002). This is supported by research that has identified a link between the impaired modulation of monoamines (serotonin, neuroadrenaline, and in particular, dopamine) and declining cognitive working memory and processing speed in older adults (Arnsten & Li, 2005; S. C. Li, Lindenberger, & Sikström, 2001). Furthermore, age-related decline in gross and fine motor performances has been associated with degenerating neuromodulation of dopamine (Seidler et al., 2010). Thus, Li et al. have proposed a theory of cognitive ageing that cuts across neurobiological, neural information processing, and behavioural levels (S. C. Li et al., 2001; S. Li, Lindenberger, & Frensch, 2000), which may also explain motor control decline in ageing. This theory proposes that deficient neuromodulation is related to noisy neural information processing and poor cortical representations of information processing functions (working memory and attention regulation), that may underlie the age-related cognitive deficits observed at the behavioural level (S. C. Li et al., 2001). This deficient neuromodulation could be related to deeper mid-brain dysfunction, representing subclinical Parkinson's disease impairment.

Alternatively, the Hemispheric Asymmetry Reduction in Older Adults (HAROLD) model of cognitive ageing (Cabeza, 2002) was proposed to explain why cognitive tasks (memory, perception and inhibitory tasks) that are associated with lateralised activation in the left prefrontal cortex (PFC) in young adults, are associated with increased bilateral PFC activations in ageing adults (Dolcos, Rice, & Cabeza, 2002). For example, functional neuroimaging studies have shown more lateralised activity in the left PFC of younger adults on tasks of verbal working memory, and right lateralised activity on tasks of spatial working memory (P A Reuter-Lorenz et al., 2000; Smith & Jonides, 1999). However, in older adults, positron emission tomography (PET) imaging shows more global bilateral activation in older adults on both verbal and spatial working memory tasks (P A Reuter-Lorenz et al., 2000). These increased bilateral patterns of activity may reflect age-related deficient neural processing in specialised and localised brain regions, supporting the dedifferentiation hypothesis.

However, others have proposed that increased bilateral activation with ageing may be a compensatory strategy in which additional or alternative neural networks are recruited in order to preserve task performance (Cabeza et al., 2002; Martins, Joanette, & Monchi, 2015; P A Reuter-Lorenz et al., 2000). This is in line with the compensatory hypothesis view. Recently, Martins et al. (2015) have proposed a Temporal Hypothesis for Compensation whereby speed of processing is compromised by delayed cerebral responding in order to maintain cognitive function. However, most compensation theories to date propose that the ageing brain is plastic and adapts to the challenges of degenerating neural motor control with compensatory network responses to maintain cognitive function (Cabeza et al., 2002). These compensatory models are also supported by neuroimaging research evidencing simultaneous cortical shrinking (including loss of white matter integrity) and increased neural activation in the frontal and parietal regions

of the brain (Greenwood, 2007). However, where cortical atrophy is not always exhibited with normal ageing, altered neuronal function and plasticity is commonly manifest (Moore & Murphy, 2016).

The main compensatory theories attempting to explain this loss of neural integrity and adaptation to this loss are the Posterior-Anterior Shift in Aging (PASA) model, the Compensation-Related Utilisation of Neural Circuits Hypothesis (CRUNCH) model, and the Scaffolding Theory of Aging and Cognition (STAC). The PASA model (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008; Grady et al., 1994) is based on neuroimaging evidence of a simultaneous decline in activation of ocipitotemporal regions and increased activation of the frontal regions in older adults in comparison to young adults while performing the same cogntive tasks. This functional reorganisation was first evidenced by Grady et al. (1994) with PET imaging during perceptual processing tasks, who suggested that older adults need to recruit more anterior parts of the brain (including the PFC) in order to compensate for deficits in sensory regions of the brain and maintain cognitive function performances. These findings have been replicated across many cognitive domains (including working memory, attention and visuospatial processing), where increased age-related frontal and parietal activation correlates positively with task performance–regardless of task difficulty or confidence levels of participants–while occipitotemporal activity correlates negavtively with task performance (Davis et al., 2008). Furthermore, the same pattern of compensatory neural reorganisation has been evidenced with electrophysiological recordings of reduced P3 amplitude morphologies, with an anterior shift in older adults on a working memory task (Steiner, Gonsalvez, De Blasio, & Barry, 2016).

The CRUNCH model proposes that overactivation in the brains of older adults who perform equivalent to younger adults behaviourally is a function of compensation

via neural plasticity (Patricia A. Reuter-Lorenz & Cappell, 2008). Specifically, this model states that older adults recruit more neural resources than young adults when task demands are low, but show less distinctive patterns of activity when task demands are high, due to limited resources: i.e. they have reached a resource ceiling (Carp, Gmeindl, & Reuter-Lorenz, 2010; Patricia A. Reuter-Lorenz & Cappell, 2008). Numerous neuroimaging studies have evidenced this pattern of compensatory overactivation to meet working memory task demands in older adults (Berlingeri, Danelli, Bottini, Sberna, & Paulesu, 2013; Cappell, K.A., Gmeindl L., 2010; Carp et al., 2010; Mattay et al., 2006).

A functional magnetic resonance imaging study by Berlingeri et al. (2013) found that older adults recruited alternate additional brain regions to complete semantic language and episodic memory tasks. When comparing the HAROLD and CRUNCH models, the authors found that the pattern of effects was more compatibale with the CRUNCH model of ageing. Carp et al. (2010) investigated verbal and visual working memory encoding, maintenance and retrieval in young and older adults using *f*MRI and multi-voxel pattern analysis. Interestingly, the results of this study actually supported both the dedifferentatuion hypothesis and compensation CRUNCH model in that they observed less distinctive patterns of activity in the sensory cortex during encoding and retrieval, but higher prefrontal and parietal dsitinctiveness at lower (simpler) task loads, and less distinctveness at higher task loads (the younger adults showed more).

The STAC model (Park & Reuter-Lorenz, 2009) of neurocognitive ageing is in agreement with the CRUNCH model, and offers one of the most comprehensive accounts of age-related neurocognitive decline and plasticity (P. A. Reuter-Lorenz & Park, 2010). This theory is unique in that it presents a model of neural activation that is continuous across the lifespan, highlighting parallels between neural development in childhood and neurodegeneration in later life (Patricia A. Reuter-Lorenz & Park, 2014). This model

proposes that compensatory functional reorganisation (including dedifferentiation) in the form of alternate neural circuit scaffolds occurs in response to age-related degradation of neural structures and networks. This can be evidenced as overactivation primarily in the frontal regions of the brain, but also parietal and mediotemporal and occipital regions, in order to maintain cognitive functionality (P. A. Reuter-Lorenz & Park, 2010).

1.4.2 Explaining age-related cognitive and motor decline

In light of these simultaneous age-related declines in cognitive, sensory and motor function, three previously proposed theoretical explanations lend themselves to elucidating the relationship between cognitive decline and falls in older adults (K. Z. H. Li & Lindenberger, 2002). First, it is possible that there is a common cause affecting sensory function and cognition (Baltes & Lindenberger, 1997), and gait and cognition in ageing adults with MCR syndrome, MCI and dementia. Second, there may be increasing overlap in resource capacities for each of these functions with ageing, resulting in cross-domain resource competition and compensatory trade-offs. This is in line with the brain and cognitive resource capacity theories above. The third explanation is a combination of both of the above may contribute to falls and declining cognition in older adults.

Therefore, it may be the case that cognitive and motor control share the same underlying pathological burden with ageing, which would account for combined impairments in those with MCR syndrome (Hausdorff & Buchman, 2013). Alternatively, as age-related cognitive *or* motor neural degeneration requires more global recruitment of other regions and networks of the brain, this may reduce resource capacity for allocation to both cognitive and motor aspects of walking and navigating. Cognition and motor function may be interdependent, with musculoskeletal and motor neural degeneration requiring more cognitive top-down input to compensate for reduced motor

control (K. Z. H. Li & Lindenberger, 2002; Liu, Chan S.Y., & Yan H., 2014). Thus, cognition may be a mediating factor of sensorimotor decline and falls, whereby attention and executive resources may be allocated to compensate for declining mobility (Woollacott & Shumway-Cook, 2002). Although, others have argued that reduced mobility could also increase the speed of cognitive decline due to reduced physical activity, social engagement and leisure activities (Demnitz et al., 2016). As with all associative research (including the cross-sectional and longitudinal studies above), the problem of causality remains a limitation for interpretation and generalisability that cannot be overlooked.

1.5 Cognitive-Motor Dual-Task Research

The dual-task (DT) paradigm has been employed to investigate the effect of simultaneously completing a cognitive task while walking (see Chapter 2 for theoretical explanations of the dual-task effect). This paradigm allows for the examination of the role of higher-level cognitive processes on walking gait control, by examining the dual-task "cost" or change in performance from single-task to dual-task conditions. The role of attention and other higher-level cognitive functions in gait control have become apparent in the DT literature (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2008). Numerous studies have evidenced greater DT costs on gait performance in older adults compared to young adults, that are more pronounced in older adults with a history of falls, MCI, dementia and post-stroke (Bowen et al., 2001; Montero-Odasso et al., 2009; Segev-Jacubovski et al., 2011; Yang, Chen, Lee, Cheng, & Wang, 2007). These impaired groups most commonly exhibit slower gait speed and increased gait asymmetry while walking with a dual-task (J. H. Hollman, Kovash, Kubik, & Linbo, 2007; Morris et al., 2016). The above shared capacity theories would suggest that these changes

in DT gait performance are a result of shared cognitive resources being redirected from gait control to the secondary task (Pashler & Johnston, 1998). Recent reviews highlight the numerous cognitive tasks affecting gait control during dual-tasking, and these findings are discussed further in the following chapter introductions (Chapters 3, 4, 5 and 6).

In sum, many varied cognitive tasks have been evidenced to affect dual-task gait, while others still have not (Bock, 2008). However, it appears that executive domain tasks specifically play an important role in gait control during dual-tasking (Al-Yahya et al., 2011; Chu, Tang, Peng, & Chen, 2013; Gomes et al., 2016; Hsu, Nagamatsu, Davis, & Liu-Ambrose, 2012). This corroborates cross-sectional and longitudinal research highlighting that executive control abilities predict fall status, gait ability and progression of decline in older adults (Herman, Mirelman, Giladi, Schweiger, & Hausdorff, 2010; Killane et al., 2014; Mirelman et al., 2012; Muir, Gopaul, & Montero Odasso, 2012b). However, executive control is a broad system, as outlined above, and is comprised of numerous attentive control processes, and associated with various cortical inputs (Yogev-Seligmann et al., 2008) that are targeted by distinct and varied tasks (tasks of sustained attention, inhibitory control, visuospatial processing, working memory and information updating). Very few studies have compared the relative impact of various executive or non-executive domain tasks, and thus the specific mechanisms underlying gait control remain unclear.

1.6 Neuroimaging single and dual-task gait

Recently, neuroimaging techniques–such as functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS) and electroencephalography (EEG)–have also been utilised to probe the neural mechanisms underlying the cognitive-motor link for gait control and falls. Electrophysiological research has revealed an

association between physical activity in older adults and the P3 event-related potential (ERP) associated with executive functions of working memory and inhibition (Chang, Huang, Chen, & Hung, 2013; Fong, Chi, Li, & Chang, 2014). More specifically, fall-risk in older adults has been associated with greater N1 and P3 ERP amplitudes for poorer inhibition of task-irrelevant stimuli on a visuo-spatial attention task (Nagamatsu, Munkacsy, Liu-Ambrose, & Handy, 2013). Research using MRI has also shown that reduced matter volumes in the prefrontal areas of the brain are associated with slower gait speeds in undiagnosed older adults, and that slower gait may be a result of age-related changes in cognitive processing speeds (Rosano et al., 2012; Rosano, Aizenstein, et al., 2008; Rosano, Brach, Studenski, Longstreth, & Newman, 2007).

Some studies have also undertaken the difficult task of measuring patterns of neural activity during single-task and dual-task walking in older adults. A functional near-infrared spectroscopy (*f*NIRS) study by Harada et al. (2009) found single-task gait speed control in older adults was associated with increased activation (oxy haemoglobin) in the supplementary motor area (SMA) and left prefrontal cortex (LPFC) of the brain, of which, the latter appeared dependent on age-related gait capacity. While other *f*NIRS studies have shown increased frontal activation (including the PFC) during dual-task walking with specific executive function tasks (Holtzer et al., 2011; Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014; Mirelman et al., 2014). Furthermore, stimulation of the LPFC in the form of transcranial direct current stimulation (tDCS) has evidenced improved postural control and dual-task gait performance in both healthy young and older adults (Manor et al., 2016; Zhou et al., 2014). EEG studies of walking reveal increased alpha and beta band frequencies in frontal and central brain regions, with modulated executive function-related N2 and P3 components during dual-task walking with an inhibitory control task (Beurskens, Steinberg, Antoniewicz, Wolff, & Granacher, 2016;

De Sanctis, Butler, Malcolm, & Foxe, 2014). Furthermore, spectral power analyses of EEG data reveal gait-related changes in the anterior cingulate cortex, posterior parietal cortex and sensorimotor cortex (Gwin, Gramann, Makeig, & Ferris, 2011).

Taken together, these findings suggest a strong link between higher-level cognitive processes, their associated frontal cortical regions of the brain, and the control of gait during both single- and dual-task walking. Overall, this is in line with the resource capacity central executive model of dual-tasking and the PASA, CRUNCH and STAC compensatory theories of neurocognitive ageing presented above, suggesting a greater need for adaptive frontal cognitive control of gait with ageing, and increased cognitive-motor load in both young and older adults.

1.7 Knowledge Gap and Implications

A fundamental problem with the cognitive-motor research presented above is that neither gait nor cognition are unitary constructs, and the problem of methodological variability has been highlighted in recent reviews. As was outlined above, gait performance can be defined by a number of spatiotemporal characteristics falling within distinct gait domains (Lord et al., 2013). Equally, cognition is a term that encompasses a myriad of mental processes ranging from language to memory and executive functions (to name a few). Much of the cross-sectional and longitudinal research has considered gait speed as a global parameter of gait, while many have used MMSE® scores as indicators of global cognition (Demnitz et al., 2016). It is important to note that the MMSE® was designed and validated as a screening tool for MCI and dementia, and not as a global measure of cognitive ability. Furthermore, much of the earlier DT research has only used one cognitive task, without justification or discussion of the specific cognitive domain being targeted, or the complexity of the task. Where studies have made comparisons between

tasks, they tend to compare tasks within the same domain, or tasks which tax multiple domain functions (Wrightson, Ross, & Smeeton, 2016), without comparative control dual-tasks. For example, Wrightson et al. compared two tasks to examine the effects of cognitive-task type, but used two tasks of working memory (serial subtraction and n-back tasks), finding no differences between the tasks, with no comparison to a different EF domain task or a non-EF control task.

The dual-task research reviews have also highlighted that the problem of high methodological variability in both the gait assessment and dual-task protocol (Al-Yahya et al., 2011; Holtzer, Wang, & Verghese, 2012; Patel & Bhatt, 2014). This heterogeneity makes comparison across studies difficult, thus limiting our understanding of the role of cognition in falls, and hindering the translation of this body of research to the clinical setting for novel interventions and rehabilitation (Worden, Mendes, Singh, & Vallis, 2016). While cognition has recently been considered a risk-factor for falls, initial attempts to apply general or non-specific cognitive screening and intervention training tasks have revealed varying effects and inconsistent results (Menant, Schoene, Sarofim, & Lord, 2014; Plummer-D'Amato et al., 2008). The vital gap in the research lies in establishing which *specific* higher-level cognitive processes underlying gait control.

1.8 Thesis aims and overview

Overall, this research aims to advance our understanding of the specific cognitive and neural processes underlying walking gait control, and how these processes are impaired in older adults and stroke survivors with a high risk of falling. Stroke survivors have a higher fall incidence rate than age-matched controls (Jorgensen & Jacosen, 2002; Simpson, Miller, & Eng, 2011), with one study reporting that up to 73% fall post-discharge: i.e. +6 months post-stroke, at the motor recovery plateau and after

physiotherapy discharge (Forster & Young, 1995; Mackintosh, Goldie, & Hill, 2005). Community-dwelling chronic stroke survivors have also previously been evidenced to require disproportionate attention while walking (Smulders, van Swigchem, de Swart, Geurts, & Weerdesteyn, 2012), and while more studies are now investigating the effects of dual-task tests and interventions in stroke patients, the role of cognition in chronic stroke is still largely understudied. For this reason, we extended our inquiry beyond diagnosis-free older adults to clinical stroke survivors as a higher fall-risk sample.

With a better understanding of the specific cognitive processes underlying gait, we hope to identify a neuropsychological computer-based task targeting the specific higher-level cognitive processes required for successful gait. Such a task could be developed further as a screening measure for falls in older adults. If we can identify a specific cognitive or neural marker of gait impairment and fall-risk, this could then lead to the informed development of alternative cognitive/neural fall screening assessments and rehabilitation programmes for stroke patients and the wider older adult population of Ireland.

The specific thesis aims are:

- To compare specific higher-level cognitive performances across healthy older adults, older adults with a history of falls, and high fall-risk stroke survivors, and relate these to specific measures of linear walking gait (e.g. speed, stride time, variability, etc);
- To identify the specific impaired cognitive functions in older adult fallers and adults post-stroke;

- To investigate the underlying neural markers of cognitive decline associated with gait and fall-risk, using electrophysiological event-related potential (ERP) analysis during cognitive task performance;
- To evaluate the efficacy of specific PC-based neuropsychological cognitive assessments to identify fallers from non-fallers (across older adult and clinical stroke samples).

1.8.1 Thesis overview

Chapter 2 provides a comprehensive overview and detailed discussion of the methodologies used throughout this thesis, including details of the cognitive, electrophysiological and gait assessment and analysis techniques. Chapter 3 describes a dual-task experiment in two groups of healthy young adults that compares the effects of multiple cognitive tasks (executive and non-executive) on dual-task gait performance over two different walkway distances (5m and 15m). The following experiment in Chapter 4 compares the same cognitive dual-tasks as Chapter 3, but in a group of healthy young and older adults, assessing the effect of age and specific cognitive domain processes on DT gait capacities. Chapter 5 presents an experiment comparing healthy young adults, healthy community older adults, and community older adult fallers on single-task gait performances, multiple executive task abilities, and the executive-associated neural ERPs. Chapter 6 describes an experiment investigating single and dual-task gait and cognitive performances on different executive tasks in healthy older adults and stroke survivors, with comparisons of cognitive-associated ERPs recorded during single-task cognitive performances. Finally, Chapter 7 will provides a general discussion of the overall results and conclusions of the work presented in this thesis, with consideration of some general limitations and suggestions of future directions.

Chapter 2

General Methods

Overview

A number of measures were employed repeatedly throughout the experiments of this thesis. These key measures used can be broadly categorised as control measures, tasks of cognitive performances, electrophysiological measures of brain activity, and quantitative measures of gait. The purpose of this chapter is to provide an outline of each of these measures, to provide more detail than is feasible within the individual experimental chapters for some, and to give some justification for why these particular methodologies were employed in this thesis.

This chapter commences with a description of the control measures that were used for all experiments in this thesis; including details on the materials, administration and scoring of each (section 2.1). Discussion of the dual-task paradigm employed and the behavioural cognitive measures used therein follows in section 2.2. The software used to generate and record responses for these computer-based tasks is detailed here. However, as the choice of specific cognitive tasks (or features of these tasks) varied across experiments, further details will be provided within the experimental chapters as necessary. Section 2.3 discusses electrophysiological measures of neural activity. Electroencephalogram (EEG) signal recording, the neurophysiological basis of this measure, equipment application, and event-related potential (ERP) data processing are all described. Section 2.4 details the measurement of quantitative gait, including specifications of the hardware, its application, and recording process. An outline of the data processing algorithm employed to extract meaningful gait outcomes from the raw data is also provided. A brief overview of the statistical analysis procedures used for all variables is then outlined in section 2.5. Finally, participant recruitment procedures and ethical approval protocols are discussed, as relevant to this thesis (section 2.6).

2.1 Control Measures

2.1.1 Mini Mental State Examination

The Mini-Mental State Examination, 2nd Edition™ (MMSE®-2™: Folstein, Folstein, & McHugh, 1975), was used in this research as a measure of global cognitive function in older adults and patients post-stroke. The MMSE®-2™ has the same assessment structure and scoring as the original MMSE®, which was first formalised as an applicable 11-item screening measure for cognitive mental impairment in psychiatric patients, and for persons with dementia (Folstein, Folstein & McHugh, 1975). Today, the MMSE® is one of the most widely used objective screening tools of dementia, and is also used in clinical research for screening inclusion/exclusion criteria, and as a clinical outcome measure (Spreen & Strauss, 1998). The test can be administered in 5-10 minutes, with one point scored per question item or task (total score: 30), with failures to respond marked as errors. Higher scores are indicative of higher cognitive functioning. One major advantage of this instrument is that it is easy to administer with pen and paper, and can be administered in many different settings (community and care). For copyright issues, this assessment cannot be included in the Appendices.

The MMSE® includes measures of orientation to time and place, language, attention, calculation, and immediate and delayed recall (Spreen & Strauss, 1998). Folstein et al. originally devised the instrument to consist of 5 domains: orientation, registration, attention and calculation, recall, and language. Further factor analysis studies of the MMSE® have revealed 5 common core components consisting of concentration/ working memory; language and praxis; orientation; verbal recall/memory; and attention span (Jones & Gallo, 2000; Banos & Franklin, 2002), which are in line with the measures originally outlined.

Initial studies showed high test-retest reliability in non-demented and demented patients (Folstein, Folstein & McHugh, 1975). However, the MMSE® is most effective at ruling out dementia diagnosis only, with very limited value in diagnosing mild cognitive impairment (MCI) among healthy controls (Mitchell, 2009). The first validation study reported that no cognitively healthy older adult patients (n=63) with 8 or more years of education scored below 24, and so this became a cut-off value for identifying impairment (Folstein, Folstein & McHugh, 1975; Lezak, Howieson & Loring, 2004). However, age and education have been shown to have a strong influence on MMSE® scores: scores decrease with age, and increase with education (Lezak & Howieson, 2004). Some cut-off points for age and education levels have been suggested, but these alterations affect the sensitivity and specificity of the measure (Spreen & Strauss, 1998), with cut-off scores now varying between 23-27 (Bryant et al., 2009; Lopez, Charter, Mostafavi, Nibut & Smith, 2005). The MMSE® has also been criticised as being biased towards verbal language items (Staruss, Sherman & Spreen, 2006), and evidences poor sensitivity in detecting MCI (Mild Cognitive Impairment; with MCI scores above 26; Nasreddine et al., 2005) and subtle impairments in samples such as patients post-stroke (Duffin, Collins, Coughlan, O'Neill, Roche & Commins, 2012).

However, the MMSE® still remains one of the most widely used objective screening measures of cognitive impairment. Kenny et al. (2013) recently provided normative values of MMSE® scores for community-dwelling older adults (5,842 adults aged 50+ years), without Parkinson's disease or severe cognitive impairment, living in Ireland. These normative values (as part of The Irish Longitudinal Study on Ageing: TILDA) are stratified by age and education level, and showed no effect of sex within this Irish sample. Kenny et al. conclude that MMSE® scores do not discriminate cognitive functions well in cognitively intact individuals, but can identify the lowest performing

percentiles in most subgroups (at the 5th and 10th percentile). MMSE® scores are used in this thesis solely as an indicator of global cognitive functioning for comparison between groups (to ensure homogeneity), and not as a variable of interest.

2.1.2 Montreal Cognitive Assessment

The Montreal Cognitive Assessment (MoCA: Nasreddine et al., 2005) is a more recently developed clinical tool of global cognitive assessment. The MoCA was devised as a more sensitive additional or alternative tool for the MMSE®, specifically for detecting MCI in people scoring between 24 and 30 on the MMSE®. Similar to the MMSE®, the MoCA is a one-page test containing 30 possible points, can be administered in approximately 10 minutes, and is also available in multiple languages (see Appendix A). The cut-off point of 26 is suggested for the MoCA for identifying MCI from normal ageing (Nasreddine et al., 2005). This test is more akin to a neuropsychological assessment, containing questions and tasks across the eight domains of: visuospatial/executive, naming, memory, attention, language, abstraction, delayed recall, and orientation.

The MoCA evidences good construct validity, corroborating the 6 cognitive factor domains of the task (Freitas, Simoes, Maroco, Alves & Santana, 2012). Furthermore, the increased focus on the executive and attention domains within the MoCA may increase its sensitivity for detecting forms of dementia other than Alzheimer's disease (Smith, Gildeh & Holmes, 2007). One study in the United Kingdom prospectively validated the MoCA for predicting dementia diagnosis within a memory clinic (Smith et al., 2007). More recently, the MoCA was tested in MCI (n=90) and AD patients (n=90) matched with healthy older adult controls (Freitas, Simoes, Alves & Santana, 2013). The findings revealed consistently higher accuracy in discrimination between MCI and AD diagnosis–in comparison to the MMSE®–with increased sensitivity, specificity, predictive value

and classification (using a cut-off of 22 for MCI and 17 for AD). When tested in both clinical and non-clinical populations, one study showed MoCA reliability to be very low in non-clinical groups, but high in the clinical group (Bernstein, Lacritz, Barlow, Weiner & DeFina, 2011). This indicates that while the test is useful beyond the clinic, the MoCA may work best for identifying and quantifying cognitive impairment in clinical patients (Bernstein e al., 2011). However, initial validity and test-retest reliability reports of the MoCA (using a cut-off of 26; 2005) and further studies since have corroborated that the MoCA shows more sensitivity and higher classification accuracy for detecting MCI from healthy ageing, when compared to the MMSE® (Damian et al., 2011; Nasreddine et al., 2005; Roalf et al., 2013).

On the whole, the MoCA has been shown to be an appropriate tool for cognitive screening, and was used within this thesis (in combination with the MMSE®) for comparison of global cognitive scores, to compare the homogeneity of the groups on broad cognitive function. Kenny et al. (2013) have also provided normative values of MoCA scores within an Irish community-dwelling older adult sample (5,802 individuals aged 50+ years). These normative values showed median scores 1 to 2 points higher than those previously reported in the Dallas Heart Study (Rossetti, Lacritz, & Cullum, 2011), highlighting the need for nationally representative normative values.

2.1.3 National Adult Reading Test

The National Adult Reading Test (NART; Nelson, 1982) is a widely used vocabulary-based measure of premorbid intellectual function. Participants are asked to orally read a list of 50 phonetically irregular English language words from a sheet of paper (see Appendix B). The everyday frequency of use of the words varies so that some words are likely to be unfamiliar to most adults. Responses are either correct or incorrect. Accuracy

scores give an indication of range of vocabulary, which correlates best with overall mental ability. The number of errors is recorded and can be used to estimate (via regression equations) Verbal IQ, Performance IQ and Full Scale IQ via a conversion table in the NART manual (Nelson & McKenna, 1975; Nelson & Willison, 1991; see Appendix C).

The high correlation between reading ability and intelligence in the normal population (Crawford, Stewart, Cochrane, Parker & De Lacey, 1998) allows the NART to determine estimates of intellectual function. NART scores correlate significantly with education (r = 0.51) and social class (r = 0.36; Crawford, Moore, Cameron, 1992), and have been shown to be a better predictor of premorbid functioning than the WAIS-R Vocabulary subtest (Collins, 2000; Petito, 2000). While age has also been correlated with NART scores, this factor accounted for very little of the variance (Crawford, Stewart, Garthwaite, Parker, & Besson, 1988).

2.1.4 Falls Efficacy Scale-International

The Falls Efficacy Scale-International (FES-I: Yardley et al., 2005) was used for all older adult sample participants in this thesis. Yardley et al. developed this international scale, building on the FES (Tinetti, Richman & Powell, 1990), to measure level of concern about falling during everyday indoor and outdoor activities, and social activities. Fear of falling has previously been identified as a psychological factor associated with increased risk of falls in older adults (Delbaere et al., 2010; Friedman, Munoz, West, Rubin & Fried, 2002; Young & Williams, 2015). This measure was used to ensure that fear of falling was not a factor in differentiating between faller and non-faller groups in the current thesis.

The questionnaire consists of 16 items of daily living activities (e.g. getting dressed or undressed, preparing simple meals, walking on a slippery surface) and asks the participant to indicate on a 4-point Likert scale how concerned they usually are about

falling while completing the activities (see Appendix D). A score of 1 indicates “not at all concerned”; 2 indicates “somewhat concerned”; 3 indicates “fairly concerned”; and 4 indicates “very concerned” (total score = 64). Delbaere et al. (2010) provided cut-off scores for the 16-item FES-I used here: low concern = 16-19, moderate concern = 20-27, high concern = 28-64. The FES-I is a short and easy to administer measure that has been shown to be highly valid and reliable (Delbaere et al., 2010; Yardley et al., 2005) even across different cultures and languages (Kempen et al., 2008).

2.1.5 Fall History

A fall history was obtained using a one-page self-report questionnaire that was designed to identify fall events in the previous 12 months (See Appendix E). A definition of a fall (adapted from Feder et al., 2000; and Tinetti, Baker, Dutcher, Vincent & Rozett, 1997) was provided at the top of the questionnaire and explained by the experimenter: “*A sudden, unintentional change in position resulting in landing at a lower level (floor, ground or on an object), other than as a consequence of health/medical issues (sudden paralysis, epileptic seizure, medications, other sicknesses) or overwhelming external force*”. Following this definition, the first question asks if the participant has experienced a fall in the previous 12 months ("yes"/"no" check box answers were required). If the response is “no”, all other questions were not applicable (N/A). If the response is “yes”, four follow-on questions ask if there were multiple falls, if there were any fall-related injuries, if medical attention was sought for a fall (as indicators of severity), and what they considered to be the primary cause of the fall. This questionnaire was solely designed to determine fall occurrence/frequency, severity, and suspected cause, in order to categorise participants into “faller” and “non-faller” groups. A participant was classified as a faller if they experienced at least one fall in the previous 12 months.

2.2 The Dual-Task Paradigm

The dual-task paradigm allows us to empirically examine the role of higher-level top-down cognitive processes on gait and balance control, and numerous studies and reviews have been conducted to date (Al-Yahya et al., 2011; Hausdorff, Schweiger, Herman, Yogev-Seligmann, & Giladi, 2008; Woollacott & Shumway-Cook, 2002, also see relevant Chapters 3, 4 and 6). The DT paradigm examines behavioural performances while two tasks are being carried out simultaneously: for example, assessing a participant's gait while they walk and complete a secondary attention-demanding cognitive task. By also measuring performances on each task individually (under single-task conditions), we can investigate the impact of one task on the other and the overlap of attentional resources needed for both during dual-tasking. The change in performance from single to dual-task conditions is calculated as the performance on the single-task minus performance on the dual-task, divided by the single-task performance, and represented as a percentage change (Bock, 2008). If performances deteriorate from the single- to the dual-task condition, this is referred to as a dual-task "cost" (DTC). Two main theoretical accounts have been proposed to explain the inability to perform two or more tasks at the same time: central bottleneck theories and resource capacity theories of attention.

1.5.1 Central bottleneck theories

Broadbent proposed a bottleneck "filter" model of information processing that prevents over-taxation of limited attentional resources (Broadbent, 1958). This model suggested that all sensory information must pass through a buffer, and then be filtered in sequence for further processing based on their physical properties. This proposes a single-channel model in which we can only attend to one type of information (or task) at a time, and so

two stimuli presented together would elicit sequential responses. This model also states that if information is not attended to or prioritised by the filter, it will decay. This was initially supported by a series of dichotic listening experiments in which participants listened to an auditory message that was shadowed by another stream of audio. While participants reported that they could hear a second auditory message, they could not recall the content of the information, thereby suggesting selective listening. Therefore, dual-task performance is impaired by the need to switch between both tasks, and keep one "on hold" in the buffer until it can be attended to (see Figure 2.1).

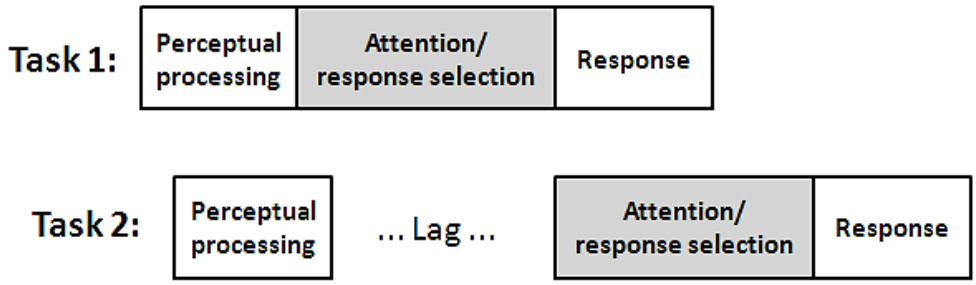

Figure 2.1. *The central bottleneck theory of attention when presented with two tasks.*

While Broadbent proposed that attention is filtered in the early stage of information processing, Treisman argued that all information is attended to, but that a filter attenuates processing of the secondary streams of information at a later stage of processing (Treisman, 1964; Treisman, Columbia, & Nagle, 1980). This was supported by evidence of the "cocktail party effect" in which secondary information, which appears unattended to, suddenly receives attention when relevant or important properties are identified. For example, this explains how at a party we can focus on the one conversation we're engaged in, but then suddenly be aware of someone using our name in another conversation across the room (Driver, 2001). This proposes that the second conversation was being partially processed, until personally relevant information (your name) is

detected and attention is switched to the secondary conversation. These filter theories would thus predict slowed walking or poorer cognitive task performance during dual-tasking, as one task is prioritised above the other, or impaired performance on both as the participant attempts to switch attention between both channels.

1.5.2 Resource capacity theories

An alternate theory of processing capacity was proposed by Kahneman et al. (1973) in which there is a limited mental resource capacity for flexibly allocating attention to multiple tasks simultaneously. When two tasks are completed simultaneously (dual-tasking), resources must be divided between both tasks (Styles, 1997). Kahneman proposed that attention can be flexibly allocated, moment to moment, but that task demands would differentially tax the limited resource capacity (Styles, 1997): i.e. two easy tasks may be sustained simultaneously, while two difficult tasks may place too much demand on available processing resources and result in poor task performances. However, it was suggested later that instead of one general resource for all processing functions, there are multiple task-specific capacities which may not overlap (Pashler & Johnston, 1998): i.e. two tasks taxing different resource capacities could be performed simultaneously without interference. Therefore, dual-task costs while walking and completing a secondary cognitive task would indicate taxation of shared underlying processes and finite overlapping resource capacities.

1.5.2.1 The Central Executive

Baddeley (1996) proposed that the ability to perform two or more tasks at the same time is a function of the central executive (or executive control) which facilitates processing of different streams of information, but within a limited capacity system. The central

executive system is one part of the "working memory" multicomponent system for the active maintenance of information (Baddeley, 1996, 2002; Baddeley & Hitch, 1974). The central executive is sub-served by the articulatory/phonological loop and the visuospatial sketchpad, which temporally store auditory, verbal and visuospatial information, respectively (see Figure 2.2). Working memory is considered as a system of both information maintenance by combining storage and processing capacities, and cognitive control which is considered one's ability to allocate limited attention where necessary and inhibit irrelevant information (Shipstead, Lindsey, Marshall, & Engle, 2014).

The central executive operates as the orchestrating control centre (or supervisory attentional system), allocating attention and resources to subsystems, or the different tasks completed concurrently during dual-tasking (Diamond, 2013). In the case of a walking dual-task, the central executive manages processing and integrating (or inhibiting) incoming bottom-up sensorimotor information, while allocating top-down attentional resources to the sensory and motor systems, and the secondary task, all while continuously tracking performance and updating information as the cognitive and walking tasks progress. Recently, a more fractional working memory system has been considered, that consists of multiple components, domains and resource capacities, associated with different brain regions, and which allows for more individual differences in strategies recruited for allocating attention (Logie, 2011; see Figure 2.1).

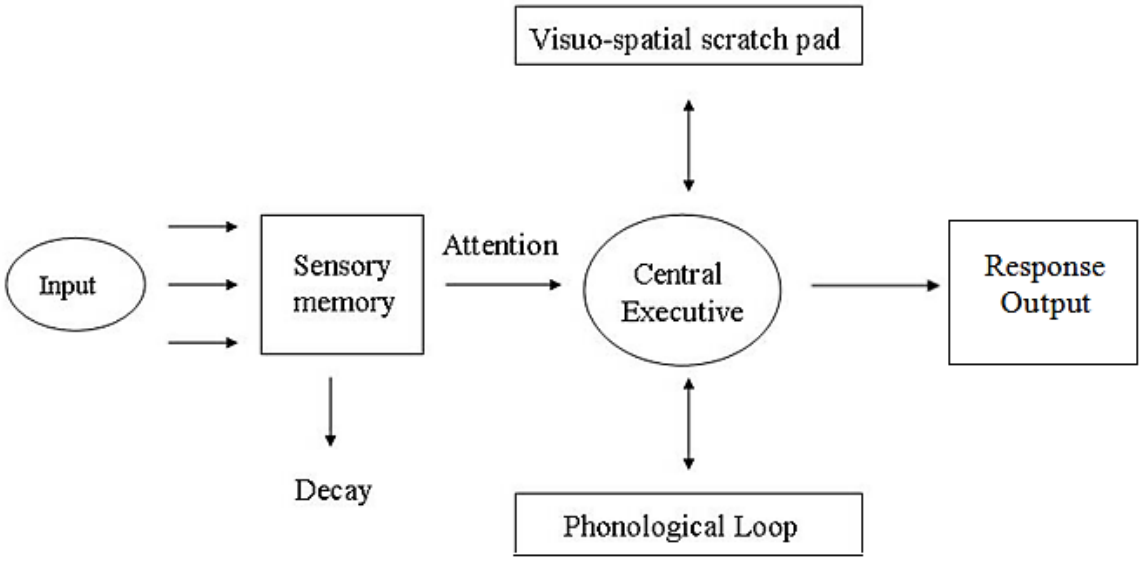

Figure 2.2.*The central executive receiving input from sensory memory, subserved by the visuospatial sketchpad and phonological loop* (Baddeley & Hitch, 1974). *Retrieved and adapted from http://www.simplypsychology.org/working%20memory.html#ce: Accessed 23/10/2016.*

The umbrella term "executive functions" is used to describe the varied top-down control processes of the central executive to manage incoming sensory information and task responses, for reasoning, problem solving and goal-oriented planning and motivation (Diamond, 2013). These control functions include working memory, cognitive flexibility (adaptability) and inhibitory control processes such as task switching (or shifting), selective attention and inhibition, information monitoring and updating (Baddeley, 1996; McCabe et al., 2010; Miyake et al., 2000): see Figure 2.3 below. The limited resource capacities of working memory and attention deteriorate with age and cognitive impairment (Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003), and have been associated with executive function-associated frontal cortical regions of the brain (Hartley, Jonides, & Sylvester, 2011).

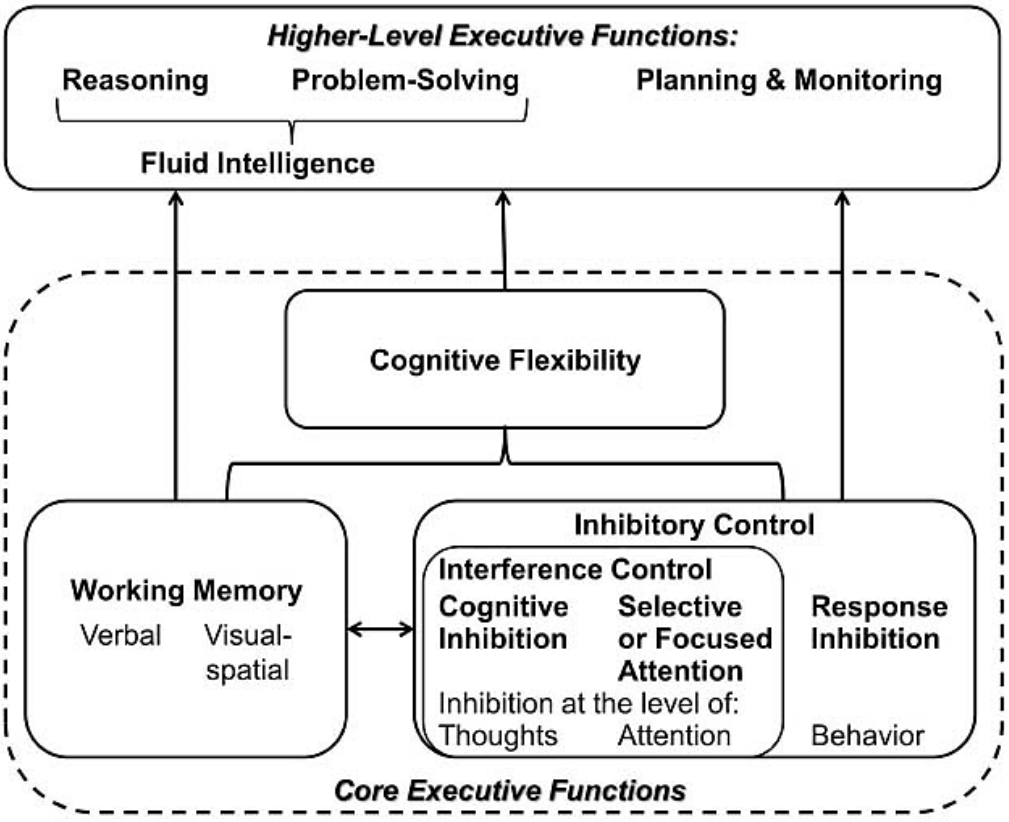

Figure 2.3 *Top-down higher-level cognitive control processes and executive functions. Taken from Lemke and Scherpiet (2015). Accessed 25/10/2016.*

2.2.1 Behavioural Cognitive Assessments

Each experiment in this thesis included a number of cognitive tasks for comparison within and between groups. Table 2.1 shows an overview of the cognitive processes assessed and tasks used in each experimental chapter. While some cognitive domains are assessed repeatedly across chapters, the specific task used or task details vary across experiments; thus, full detail of the tasks will be given within each experimental chapter. For example, the n-back task was a commonly used test of working memory in all experiments. However, for one experiment a 1-back version of this task was used, while in the others a 2-back version was employed. Furthermore, some n-back tasks used visual stimuli, others were auditory (depending on whether the task was conducted while seated or walking), and varying response windows were set depending on whether young, older

adults, or patients post-stroke were partaking, in order to set an appropriately challenging level for each sample.

Participant performance on the serial subtraction (SS) task and alphabet recitation (ABC) task was recorded with pen and paper by the experimenter (these tasks will be described later within the relevant experiment chapters). All other cognitive tasks were computer-generated, using E-Prime© presentation software (version 1.0 and 2.0). Tasks were built and run in E-Prime©, whereby visual or auditory stimuli were presented and responses (keyboard or mouse button press) were automatically logged. Accuracy (ACC) and reaction time (RT) were automatically recorded, and were the key dependent variables for statistical analyses. Accuracy (%) was measured as the number of correct responses divided by the total number of response trials, multiplied by 100. Reaction time (ms) was measured as the time between stimulus presentation and participant response, and each participant's mean RT to all trials in a task block was collated in E-Prime©. Where concurrent EEG recordings were taken, commands were also coded into the E-Prime presentation tasks to send Transistor-Transistor Logic (TTL) voltage triggers to the EEG acquisition computer. This was done via a parallel port cable connection, linking the presentation and EEG acquisition computers. These triggers allowed stimulus presentation and participant responses to be logged in real-time during EEG recording. In this way, *post hoc* time-locked ERP analysis could be carried out with the EEG signal data.

Table 2.1: *Cognitive processes assessed in each experiment of the current thesis.*

Cognitive Process	Experiment 1a+1b	Experiment 2	Experiment 3	Experiment 4
Working Memory	n-Back (auditory 2-back)	n-Back (auditory 2-back)	n-Back (visual 1-back)	n-Back (auditory 2-back)
Motor Processing	Motor Response task (auditory: 2 tones)	Motor Response task (auditory: 1 tone)	Motor Response task (auditory: 1 tone)	Motor Response task (auditory: 1 tone)
Mental Tracking/ Working Memory	Serial Subtraction task (100-3s)	Serial Subtraction task (100-3s)		
Visuo-Spatial Decision Making	Clock task (auditory)	Clock task (auditory)		
Verbal Recitation		Alphabet Recitation		
Sustained Attention/ Conflict Monitoring/ Response Adaptation			Stroop task (visual: word-colour)	Stroop task (auditory: word-pitch)

2.3 Electrophysiology

Electroencephalography is one of the oldest non-invasive extracellular recording techniques for the investigation of the electrical activity of the brain (Buzsaki, Anastassiou & Koch, 2012). Human electroencephalography stems from Hans Berger's first publications of "Elektenkephalogramm" measurements of the human brain in 1929. An electroencephalogram (EEG) records and amplifies electrical voltage currents measured at the scalp, via electrodes, and plots this over time. This scalp-recorded signal is considered a measure of electrical current fluctuations resulting from the summed activity of synaptic excitations in the cortex (Luck, 2014).

ERPs are time-locked EEG signals that are extracted by averaging across numerous trials, and are used to identify associated neural responses to sensory, cognitive and motor events (Luck, 2014). The first sensory-evoked potential (ERP) recordings in conscious humans were published by Davis and Davis in 1939 (Davis, Davis, Loomis, Harvey & Hobart, 1939; Davis, 1939). EEG-recorded ERP analysis is currently one of the most widely used methods in cognitive neuroscience to non-invasively examine the neural correlates of information processing (Nidal & Malik, 2015). A more detailed outline of the principles of EEG and the ERP analysis technique follows below.

2.3.1 Neurophysiological Basis

A scalp-recorded voltage (V_e) is generated by all active cell electrical processes within a given volume of brain tissue (Buzsaki, Anastassiou & Koch, 2012). The scalp potential is mainly elicited by synchronised post-synaptic activity from multiple neurons in the cortex (Luck, 2014). When cells fire perpendicular to the cortex, the post-synaptic potential generated from polarisation of the nerve cell membrane (referred to as local field potential: LFP), results in an accumulated voltage observable at the scalp. These post-

synaptic potentials are a result of neurotransmission, which is the process of information transfer, or communication, in the central nervous system.

2.3.1.1 The nerve cell

The two key types of cells in the central nervous system (CNS) which communicate via transmissionary electrical signals are nerve cells and glia cells. Nerve cells consist of the soma (or cell-body), dendrites, and the axon which makes contact with other nerve cells or other organs (Niedermyer & Lopes da Silva, 2005; see Figure 2.4(a) for the structural features of a common neuron). The soma contains the nucleus and houses most of the cell's protein synthesis. These proteins are transported to the cell ends and dendrites by the cylindrical axon (Sanei & Chambers, 2013). Transmission of electrical signals is enhanced by an insulating myelin sheath surrounding the electrically conductive interior of the cell (Buzsaki, Anastassiou & Koch, 2012). Electrical signals are transmitted between axons and dendrites, or dendrites and the dendrites of other cells at the synapse.

The largest contributors to EEG signals are the cortical pyramidal cells, which are mostly radially aligned and perpendicular to the cortex (see Figure 2.4(b)). Pyramidal cells in particular have a set of tree-like basal dendrites at the base of the soma, which are closer to the white matter, and an apical dendrite at the apex of the soma, which is in the direction of the cortical surface (Luck, 2014). The glia cells (surrounding the neuron soma and cell structures) also make contact with other nerve cells and vessels, and feature excitable membranes (Lopes da Silva, 2005; in Niedermeyer & Lopes da Silva, 2005).

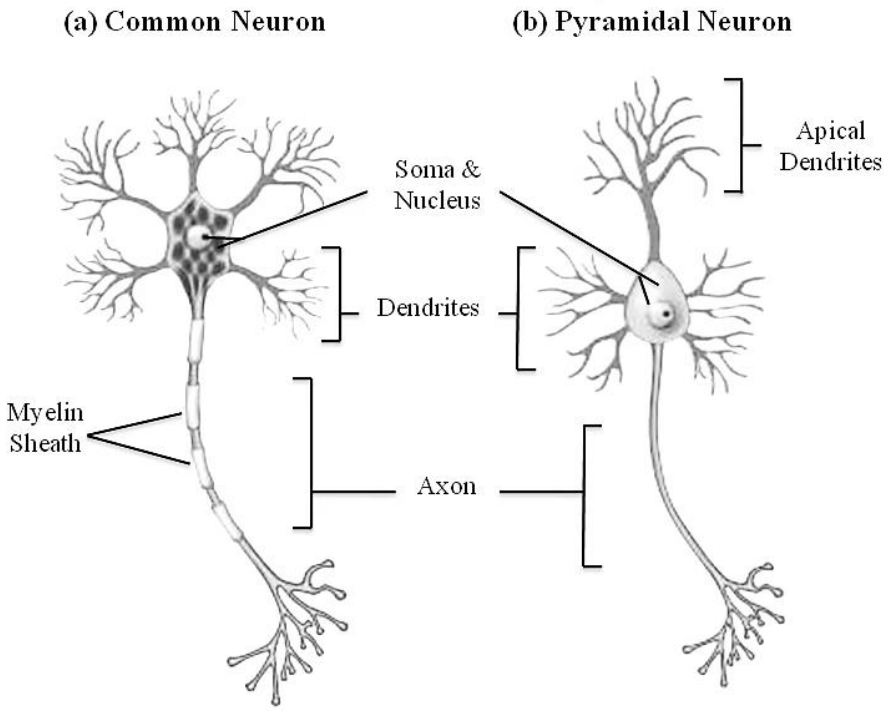

Figure 2.4: *Diagram of cell structure of (a) Common neuron and (b) Pyramidal neuron, with soma and nucleus, dendrites and apical dendrites, axon, and myelin sheath. Adapted from: http://www.wisegeek.com/what-is-a-pyramidal-neuron.htm#. Accessed: 11th August, 2016.*

2.3.1.2 Electrical potentials

Neurons produce two main types of electrical activity; action potentials (AP) and post-synaptic potentials (PSP). While a single-unit microelectrode recording can capture the action potential of a single neuron *in vivo*, the array of EEG electrodes on the scalp records the summed PSP voltage from multiple neurons. When penetrated with a microelectrode, the membrane of a cell body gives a reading of -60 to -70 mV which is more negative than outside the cell (Sanei & Chambers, 2013). This negative resting potential is maintained by a larger number of negative protein ions (anions) within the cell, balanced by sodium (Na+) and potassium (K+) positive ions (cations) in the intracellular and extracellular space of the neuron. Transient deviations from this negative resting potential (via voltage-gated Na+ and K+ channels) resulting in a more positive transmembrane

potential, indicate action potential firing or synaptic activity (Speckmann & Elger, 2005; in Niedermyer & Lopes da Silva, 2005).

An AP is a rapid (1ms) electrical current which transmits information from a nerve cell to the surrounding axons and dendrites of other nerve cells. An AP can only occur when an event causes the cell membrane to depolarise: i.e. become more positive than the resting state of -70 mV (Purves, Augustine, Fitzpatrick, et al., 2004). When this occurs, Na+ channels open and more sodium ions flow inward, making the cell depolarise further. If a cell gradually depolarises to a threshold potential of -50 mV to -55 mV, depolarisation will increase suddenly, resulting in the generation of an AP in the soma in an *all-or-nothing* fashion. Na+ channels will start to close at the peak of the AP, while K+ channels open. Potassium ions move out of the cell and the membrane quickly repolarises, with a brief hyperpolarisation (i.e. falls below -70 mV) sometimes occurring before returning to the resting state potential (see Figure 2.5).

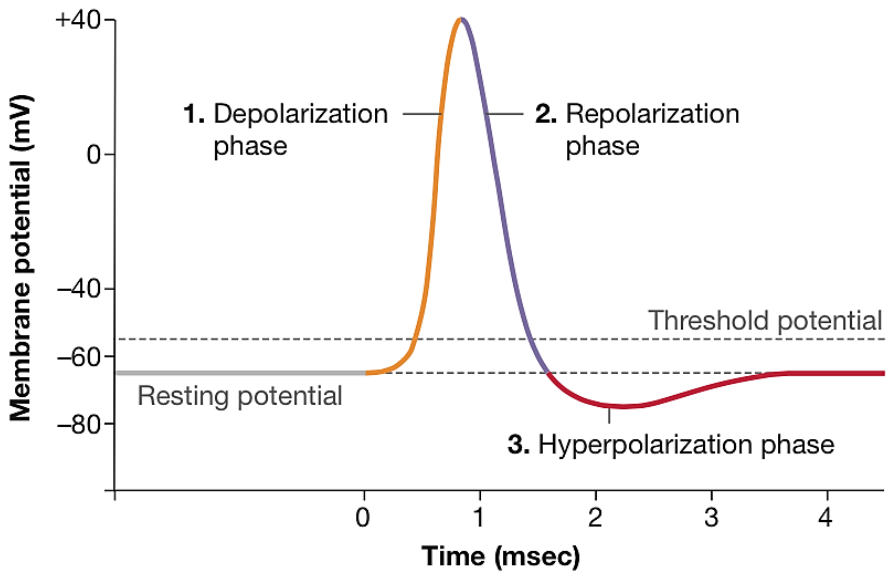

Figure 2.5: *Illustrative graph depicting the stages of an action potential in microvolts (mV: y-axis) over time (ms: x-axis), including stages: 1. depolarization; 2. repolarization; 3. hyperpolarization and resting state. Retrieved from: https://www.premedhq.com/skeletal-muscle-action-potential. Accessed 11th August, 2016.*

This AP is a discrete voltage spike generated in the soma that travels down to the axon terminals, resulting in the release of neurotransmitters into the synapse (Luck, 2014). As the neurons do not actually touch, an AP cannot transfer directly from one cell to the other (the synaptic cleft is too large). However, the chemical process of synaptic transmission elicits a subsequent excitatory or inhibitory change in the next axon membrane potential, which determines if an AP is generated in the post-synaptic cell (Luck, 2014; Sanei & Chambers, 2013). This PSP can last for approximately 10-100ms.

When an action potential travels along the nerve cell ending in an excitatory synapse, an excitatory post-synaptic potential (EPSP) will occur in the following neuron due to cell depolarisation (the post-synaptic cell becomes more positive than the resting state potential). Two action potentials travelling together, or in short succession, along the same fibre will result in a summation of EPSPs in the following neuron, which may generate an action potential in the post-synaptic cell if the membrane potential threshold is reached. Likewise, if the fibre ends in an inhibitory synapse, an inhibitory post-synaptic potential (IPSP) will occur due to hyperpolarisation, decreasing the chances of an action potential occurring in the next cell (Purves, Augustine, Fitzpatrick, et al., 2004; Sanie & Chambers, 2007; Speckmann & Elger, 2005; in Niedermyer & Lopes da Silva, 2005).

2.3.1.3 Synaptic transmission

The generation of an EPSP or IPSP depends on the type of neurotransmitter that is released into the synaptic cleft and its interaction with the corresponding receptor on the post-synaptic membrane (Lopes da Silva, 2005; in Niedermyer & Lopes da Silva, 2005). Neurotransmitters are released from the pre-synaptic neuron when an action potential arrives at the terminal, causing an influx of calcium cations (Ca2+) through voltage-gated channels in the plasma membrane (Purves, Augustine & Fitzpatrick et al., 2004). This

influx triggers exocytosis, causing the neurotransmitter vesicles to fuse with the pre-synaptic terminal membrane and release their contents into the synaptic cleft (see Figure 2.6 for an illustration of neurotransmission at the synaptic cleft).

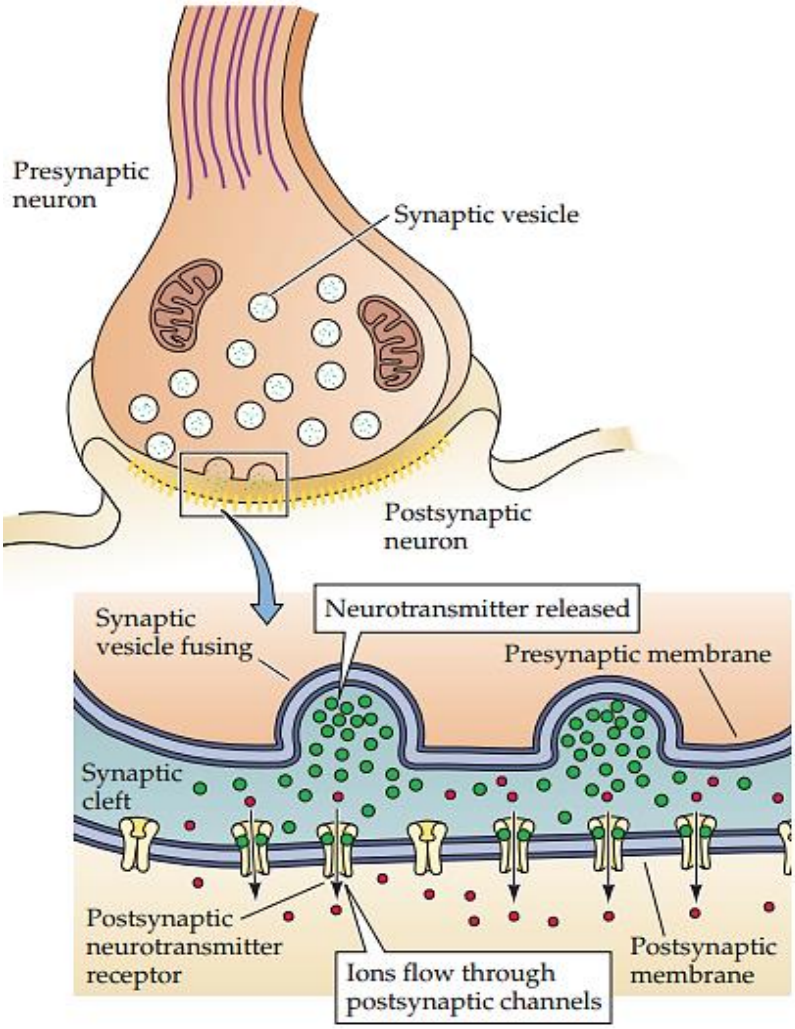

Figure 2.6: *Diagram of synaptic transmission at a chemical synapse, with pre- and post-synaptic membranes, and neurotransmitter vesicles and receptors. Adapted from: http://www.dbbe.fcen.uba.ar/contenido/objetos/NeuroscienceDalePurves.pdf. Accessed 10th August, 2016.*

These neurotransmitters diffuse across the synaptic extra-cellular space and bind to receptors on the post-synaptic membrane. This interaction triggers the opening and closing of ion channels, which changes the conductance of the membrane, and usually

produces a PSP. If an EPSP causes the post-synaptic membrane to depolarise to the -50 mV threshold, then an action potential will occur (Sherwood, 2004). The neurotransmitters that don't bind to the post-synaptic membrane are removed from the synaptic cleft by diffusion, degradation by surrounding enzymes, or reuptake by the pre-synaptic membrane or surrounding glia cells in the extra-cellular space (Purves, Augustine & Fitzpatrick et al., 2004).

EPSPs and IPSPs are differentially associated with specific ion channels which let positive or negative ions flow in and out of the cell (Lopes da Silva; in Niedermyer & Lopes da Silva, 2005). EPSPs occur when the neurotransmitter (most commonly glutamate) binds to the protein receptors AMPA and NMDA on the dendrites, opening ion channels that allow cations such as Na^+ or Ca^{2+} into the cell (Spruston, 2008). However, IPSPs occur at the soma and axon when the inhibitory neurotransmitter GABA (gamma-aminobutyric acid) opens channels for anions such as chlorine (Cl-) to flow in, or cations such as K+ to flow out (Buzsaki, Anastassiou & Koch, 2012). Consequently, when ions flow in or out of the post-synaptic cell, a sink-source configuration occurs in the extra-cellular space around the neuron. The terms *sink* and *source* are used for the sites where current flows into and out of the cell. When positive ions flow into the cell (EPSP), an active sink (negative current) is left in the synapse area, and passive sources along the soma-dendritic membrane. However, when negative ions flow into the post-synaptic membrane (IPSP), the opposite occurs: an active source remains at the synapse with passive sinks along the soma-dendritic membrane (Lopes da Silva; in Niedermyer & Lopes da Silva, 2005).

If an excitatory neurotransmitter is released at the apical dendrite of a pyramidal cell, positively charged ions will flow into the cell from the extracellular space, resulting in cell depolarisation (EPSP) and a net negativity in the surrounding area (i.e. a sink).

Current will also flow out of the basal dendrites and soma leaving a net positivity (source) in the surrounding area, and this creates a dipole of positive and negative charge. In this instance, if multiple surrounding neurons (all oriented the same) released an excitatory neurotransmitter at the apical dendrite, the summed current voltage recorded at the scalp would show a negative potential. However, there would also be a simultaneous positivity on the remainder, because the dipole has two sides (Luck, 2014). Therefore, the scalp-recorded EEG reflects the summed positive and negative current dipoles from a large group of neurons (called an equivalent current dipole).

2.3.2 ERP Components

ERP waveforms are embedded in the EEG signal and can be extracted by event-locking the EEG signal to a stimulus or response event, and averaging this across numerous trials (Luck, 2014). These averaged waveforms across trials are then averaged across all subjects to generate grand average ERP waveforms. As outlined above, these ERP waveforms are widely considered to reflect electrical potentials in the extracellular fluid generated when ions flow across pyramidal cell membranes via neurotransmission (Woodman, 2010). These waveforms reveal the temporal changes in the equivalent current dipole, and are plotted in microvolts (μV), over time (ms). The way in which these electrical currents propagate through the brain to the scalp is direct, instantaneous and offers millisecond resolution, making ERP measurement an excellent tool of temporal resolution for many sensory, perceptual and cognitive processes (Nunez & Srinivasan, 2006; Woodman, 2010). However, the distribution of the scalp signal is affected by the soft and hard tissues (e.g. the resistance of the skull) the signal must traverses from the local source potential to the recording electrode (Buzsaki, Anastassiou & Koch, 2012).

Therefore, the cortical location of a generated ERP cannot be determined by the voltages recorded by electrodes on the scalp (Luck, 2014).

The positive and negative voltage deflections (ERP components) are labelled with P and N, respectively, and a numerical indication of the order or time (ms) of the peak in the waveform sequence: e.g. N1/100, P1/P100, N2/N200 (Woodman, 2010; see Figure 2.7 for an illustrative example of some ERP components (negativity is displayed upwards in this figure). Furthermore, some components can be subdivided; for example, the P3 ERP can exhibit an earlier P3a and later P3b component which are associated with different processes and neural structures. Early ERP components, such as P1, are considered to be exogenous (externally evoked by sensory stimuli), with little influence from top-down/voluntarily-driven processing. Later components are considered to be more endogenous, influenced by top-down, controlled processes, and associated with perceptual processing, motor responding, and higher-level cognitive processes (for e.g.; discrimination, memory and decision making). In this way, ERP components are considered to exhibit how the brain processes information (the relevant components will be discussed in more detail within the experimental chapters). With an appropriate experimental design, any differences in ERP waveforms between groups or different stimulus conditions can be interpreted as differences in the underlying neural activity of information processing (Luck, 2012).

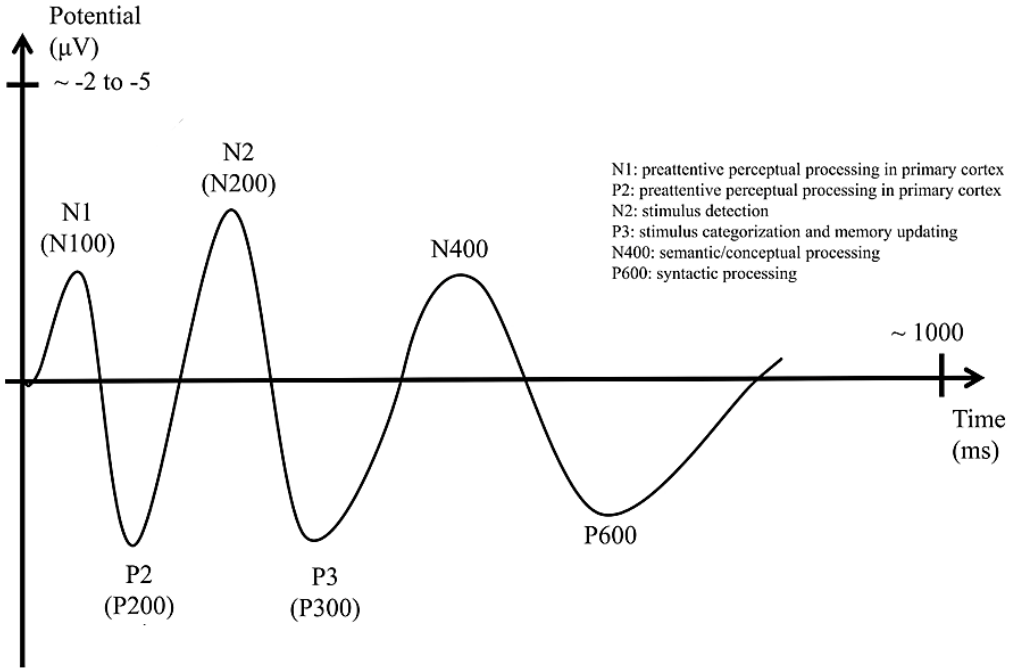

Figure 2.7. *Illustrative example of some common ERP components and their latencies, with their functional interpretation: vertical axis unit: scalp potential in microvolts (μV) with negativity upward; horizontal axis unit: time from the stimulus onset in milliseconds (ms). Adapted from: http://journal.frontiersin.org/article/10.3389/fnhum.2014.00437/full. Accessed 11th August, 2016*

2.3.3 Advantages and Disadvantages of EEG/ERP analysis for Research

One of the strengths of electrophysiological measures is that the underlying biophysics is well understood, and rigorous mathematical models have been developed to explain the relationship between the scalp-recorded ERPs and cellular currents (Grewer, Gameiro, Mager & Fendler, 2013;Buzsaki, Anatassiou & Koch 2012). However, the utility of neuroimaging techniques is usually determined by the spatial and temporal resolution of their recordings. As mentioned above, the major advantage of EEG/ERP analysis is the direct, unlimited temporal resolution of neural electrical activity in the brain. The temporal resolution of ERPs is far greater than many other techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI: Luck, 2014). These neuroimaging techniques measure regional cerebral blood flow (rCBF)

which occurs after neuronal firing, thus acting as a secondary measure indicating increased neural activity. These measures have poor temporal resolution due to the time it takes for rCBF to increase before it is recorded (taking seconds). Therefore, ERPs are useful for determining the millisecond-to-millisecond stages of information is processing in the brain.

However, the spatial resolution of PET and fMRI three-dimensional representations is far greater than the EEG signal, and these techniques can also examine activity in deeper sub-cortical regions that EEG cannot. Electrical currents diffuse, in a non-linear fashion, as they propagate through the brain, skull, meninges and scalp (following the path of least resistance). This leads to a very broad voltage distribution at the scalp (Luck, 2014). It is very difficult to definitively reverse calculate the location and orientation of the underlying equivalent current dipole (called the *inverse problem*). This is because there are an infinite number of dipole configurations which could account for the observed scalp-recorded potential: i.e. there is no *unique solution* to the *inverse problem*. This means that the EEG signal has very low spatial resolution, and this is the major methodological drawback of this technique. Some complex algorithms and computational models have been developed to attempt to localise a single equivalent current dipole generator (Grech et al., 2008). However, these methods only offer approximate solutions. Therefore, ERPs remain fundamentally better suited for determining the temporal resolution of brain processes (Luck, 2014).

There are a number of other advantages to using ERPs as a measure of neural activity. One is the non-invasive nature of EEG recording and ERP analysis, meaning there is very little discomfort for the participant. Similarly, the metal restrictions of MRI techniques do not apply to EEG testing (participants who they have metal implants can still partake). Another advantage is the relatively low cost in comparison to other imaging

techniques (such as fMRI). Furthermore, with the development of active electrodes and portable EEG recording systems, EEG testing is no longer restricted to specific laboratory settings (testing can be carried out at different sites, including the bedside).

2.3.4 EEG Application and Recording

For all experiments in which EEG was recorded for ERP analysis (Chapters 5 and 6), a BioSemi ActiveTwo measurement system was used (BioSemi, Amsterdam, Netherlands). This system consists of a 32 sintered Ag-AgCl Active-electrode ribbon for recording EEG from the scalp. These pin-type electrodes have low output impedance and mount onto a specifically designed 32-channel BioSemi head cap (fastened with a chin strap) which uses the International 10-20 system for electrode placement (American Electrophysiological Association, 1999: see Figure 2.8). In addition, 5 flat-type Active-electrodes were used for placement on the face: 1 reference electrode and 4 electrodes for recording electrooculogram signals resulting from eye movements.

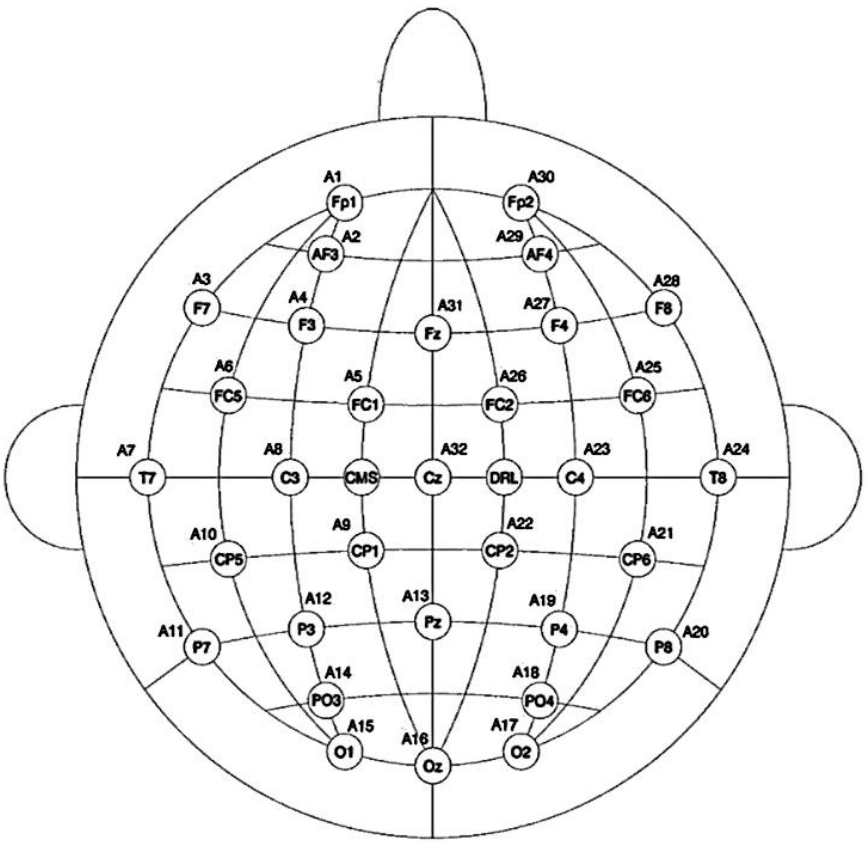

Figure 2.8. *BioSemi 32 channel cap montage according to the International 10-20 system for electrode placement. Adapted from BioSemi website: http://www.biosemi.com/pics/cap_32_layout_medium.jpg. Accessed 11th August, 2016.*

The first step was to place the head cap on the participant, taking care to ensure the midline electrodes (Fz, Cz, Pz and Oz) were positioned along the sagittal axis. A non-abrasive electro-conductive electrolyte gel (Signa Gel®) was then applied to each of the 32 electrode sites in the cap, and the 32 pin-type electrodes placed in the corresponding site. The flat-type electrodes were attached to the skin on the face using adhesive disks, with a small amount of gel applied to the electrode gel cavity to reduce motion artifacts. One electrode was placed on the nose, midpoint between the nasion and the tip of the nose, and used as a baseline reference for the scalp electrodes. Vertical electrooculogram (VEOG) signals from eye movements were recorded from an electrode placed above and below the left eye, and horizontal eye movements (HEOG) were recorded from two

electrodes placed at the temple of the face, on the outer canthus of the left and right eye (see Figure 2.9).

The 32 electrode scalp ribbon and 5 facial electrode cables connect to an AD-box (with detachable rechargeable battery) which digitises sensor signals at a 24 bit sampling resolution. These digital outputs are then sent to a Receiver−via an optical fibre cable− which converts the incoming optical data to an USB2 output. This Receiver also obtains triggers from the E-Prime presentation software on the presenting PC via a 37 pin Dub-D connector which plugs into the Receiver trigger port. Both the electrode optical data and trigger outputs are sent via a USB2 cable to the recording PC running the BioSemi ActiView acquisition program (see Figure 2.9 for BioSemi ActiveTwo system set-up). The EEG data were sampled at a rate of 1024 Hz, with a pass band filter from 0.16 Hz to 100 Hz. Analogue event triggers received from the stimulus-presentation laptop were concurrently recorded by the ActiView program.

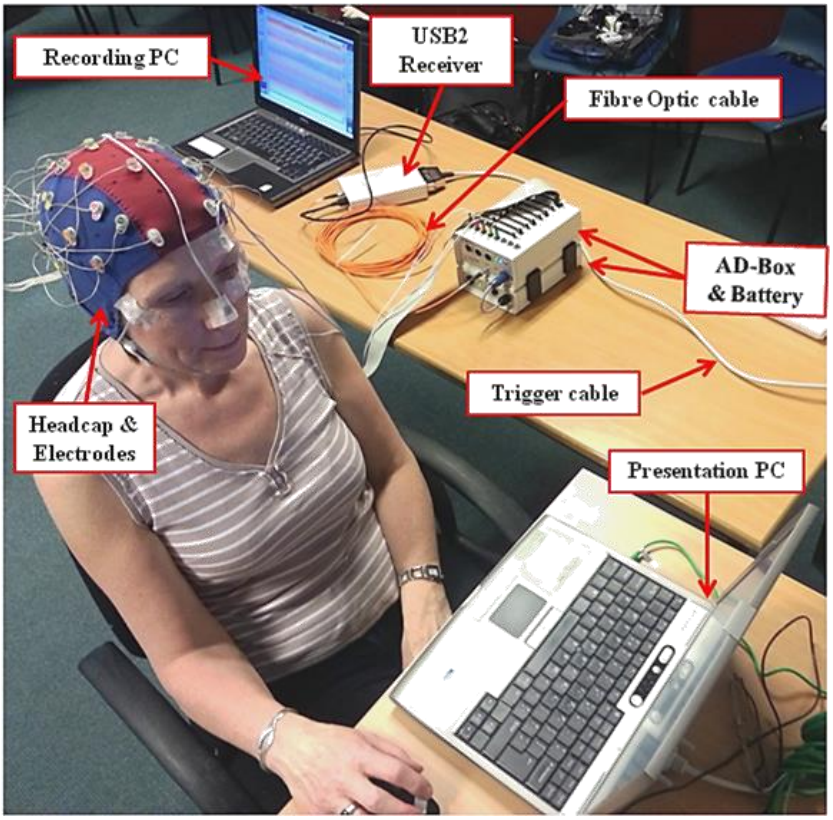

Figure 2.9. *BioSemi ActiveTwo recording system set-up with electrodes and head cap applied to participant's head. Permission for use of this image was obtained from the participant at the Department of Psychology, Maynooth University, 2014.*

2.3.5 Data Processing and Averaging

The EEG data were analyzed off-line using Brain Electrical Source Analysis software (BESA version 5.3; GmbH, Germany). The data were referenced to the nasion electrode as has been the standard practice in this lab in the past, to subtract the electrical signal and noise recorded at this base site from the current potentials recorded at each of the scalp electrodes. A notch filter at 50Hz and a 30 Hz high cut-off filter were applied off line. The four electrooculogram (EOG) electrodes were used to monitor vertical and horizontal eye movements, which were averaged offline and automatically attenuated using an algorithm in BESA (which uses an internal model of artifact topographies; Berg and Scherg, 1991; Ille et al., 2002).

Following this, the data file was visually examined for any movement artifacts to be manually removed. Any particularly noisy channels identified were interpolated from surrounding electrodes, or removed, depending on the location of electrode. Stimulus-locked ERP epochs were set and averaged in BESA. Each epoch started 200ms before stimulus presentation as a baseline correction interval. The baseline of -200ms was used as a neutral mean voltage and was subtracted from the mean ERP voltage, to control for random pre-stimulus fluctuations. The end of the epoch was determined by the behavioural response times of participants.

ERPs were averaged for each individual participant across all trials for each task condition, at each electrode site. Grand averages were then calculated across all participants in a group for each task condition. ERP components and their time windows were identified from visual inspection of an ERP waveform topography (voltage map) generated in the BESA software. ERP topographies calculate values for intermediary spatial points between electrodes on the scalp in relation to neighbouring electrodes, by means of mathematical interpolation (Handy, 2005). However, we cannot assume that the location of peak voltages on the scalp map are related to a current source generator, because we do not know how many neural generators are simultaneously active and contributing to any given ERP component (Woodman, 2010). Electrode sites showing maximal peak amplitudes were also selected for comparative analysis via visual inspection of these grand averaged waveforms. Mean amplitudes and peak latencies were the dependent variables for all statistical comparisons.

2.4 Quantitative Gait Analysis

Quantitative gait data was collected using wearable inertial measurement unit (IMU) sensors, with temporal and spatial gait variables extracted, *post hoc*, via an event-detection algorithm. The use of wearable sensors for gait analysis has advanced considerably in the past two decades, due to improved motion sensing technology, smaller sensor size, and the development of complex algorithms for processing movement signals (Tao, Liu, Zheng, Feng, 2012). IMUs can be placed on the feet or legs, and can measure various characteristics of human gait. For example, IMUs consisting of accelerometers and gyroscopes, placed on the lower limbs, can measure the acceleration and angular velocity of foot or leg movement. A kinematic analysis of the lower limb movement signal can then detect gait phases and obtain temporal and spatial characteristics of the gait cycle (Tao, Liu, Zheng, Feng, 2012).

Wearable IMU sensors were employed because they are inexpensive, can be applied easily and quickly for recording, and can be used outside of a specialized laboratory, unlike other gold-standard gait analysis methods (such as camera motion capture systems and force platform systems). The quick and non-cumbersome set up of wireless sensors was particularly important for Experiment 4 (Chapter 6), in which patients were tested in a hospital setting on a number of measures, and it was important to keep protocol time to a minimum (no more than 2 hours) for participant comfort.

2.4.1 Data Acquisition

For all instances of gait measurement, two SHIMMER™ kinematic sensor units (SHIMMER2R: Shimmer Research Ltd, Dublin, Ireland) were used. SHIMMER™ sensor units are commercially available, allow for non-invasive wireless data collection, and have been previously validated against gold-standard gait-sensing mats. Each unit

contains a tri-axial accelerometer, gyroscope, and magnetometer, allowing for integrated 9 DoF inertial sensing. After initial calibration, these units were used to transmit raw kinematic data from the accelerometer (acceleration), and gyroscope (angular velocity) to a recording computer, via Bluetooth, for off-line analysis. One unit was secured to the shank of the left and right leg using custom elasticised Velcro straps. The sensors were placed on the anterior of the shank, midway between centre of the knee joint and the lateral malleolus (see Figure 2.10 below). Each gait assessment saw participants walk along a straight, unobstructed pathway (5m, 15m or 20m in length) 4 times per trial. Participants were instructed to walk at a normal self-selected speed. The sensors were programmed in MATLAB® programming environment (http://www.mathworks.com/, Natick, VA, USA) to: start recording, sample each axis at a rate of 102.4Hz, stop recording, and save the raw data to .txt output files.

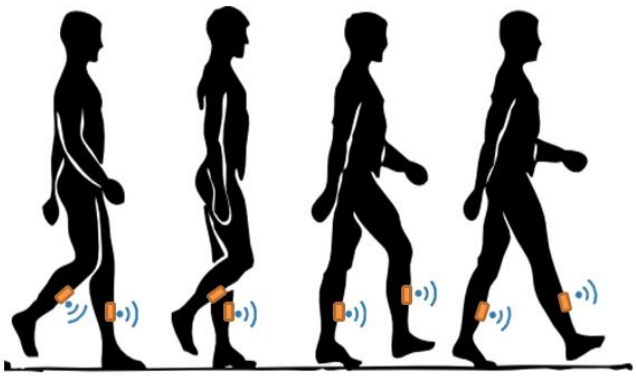

Figure 2.10. *SHIMMER Bluetooth sensor placement on the shank for gait measurement. Adapted from: https://nextlife8.files.wordpress.com/2011/06/walking.jpg. Accessed 11th August, 2016.*

2.4.2 Data Processing

All data processing was carried out by collaborator Dr Matthew Patterson of the Insight Centre for Data Analytics (University College Dublin), using a previously validated

algorithm developed in MATLAB®. This algorithm identifies gait events (heel-strike and toe-off) in the inertial data of the sagittal plane gyroscope signal from the shank (Patterson et al., 2014a; Patterson et al., 2014b). The algorithm then calculates temporal and spatial gait metrics from these gait events. This method is based on previously validated algorithms using gyroscope signals recorded from the shank (Doheny et al. 2010; Greene et al., 2010). In addition, this algorithm excluded from analysis any initial small steps before steady state walking, turns at the end of the walkway, and small steps around the turns.

The following gait metrics were calculated from the extracted gait events: gait speed (m/s), stride time (s), stride time variability (%), stride length (m) and stride length variability (%). Gait speed was defined as the distance walked in the walking time for each trial. Stride time was calculated as the time between successive heel-strikes. This is known as a single gait cycle (see Figure 2.11). Stride length was then defined as the distance covered during stride time (using knowledge of the total distance and the number of gait cycles detected from gait events). Stride time and stride length values were averaged for each foot, and then averaged across both feet for each participant. Gait cycle values were averaged, to give an overall mean value for each gait variable, for each subject. Coefficient of variation (CV) values were calculated for stride time and stride length, to determine within-subject variability. CV values were calculated using the formula: $CV\% = \left(\frac{SD}{M}\right) * 100$.

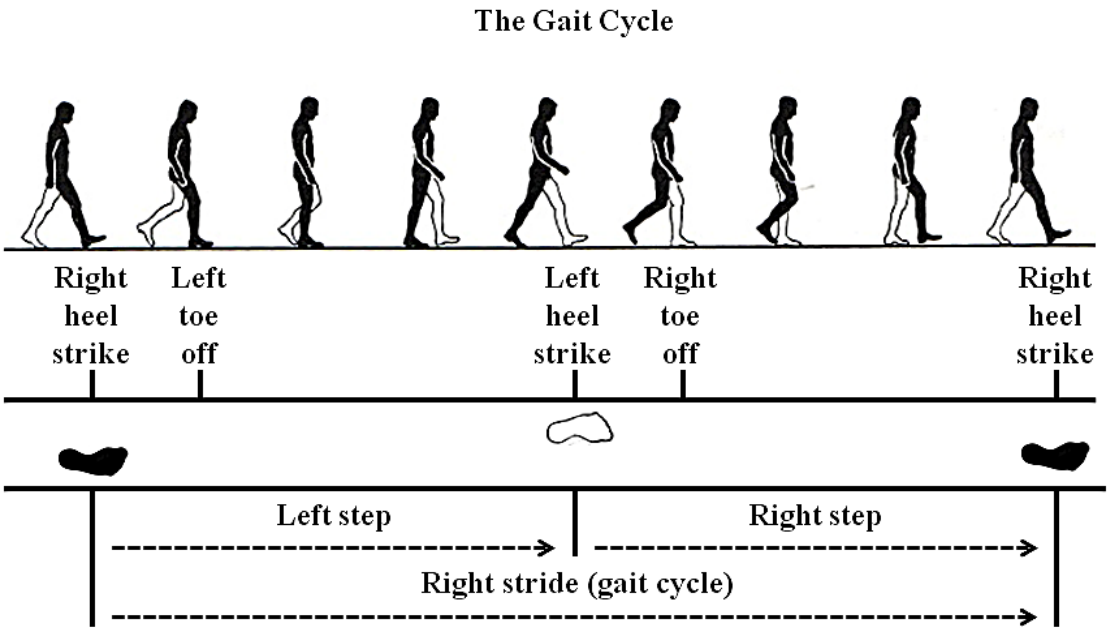

Figure 2.11. *The Gait Cycle: heel strike and toe-off gait events, and step and stride measures of a single right stride gait cycle. Adapted from: http://www2.warwick.ac.uk/fac/sci/eng/meng/nongps/rnd/gait/. Accessed 11th August, 2016.*

These five gait characteristics have been commonly used for evaluating gait in the past and have been associated with cognitive function in ageing and MCI studies (Lord et al., 2013; van Iersel et al., 2004; Verghese et al., 2007b; Verghese et al., 2008). These characteristics have also been identified to fall within different distinct domains of gait characteristics. Verghese et al. (2007; 2008) previously identified 3 gait domains of pace, rhythm and variability in older adults and MCI. More recently, Lord et al. have identified 5 domains in older adults without cognitive impairment (using an MMSE® cut-off score of 24): pace, rhythm, asymmetry, variability and postural control. Stride length, stride time variability and gait speed load onto the pace domain which is associated with attention and executive function (Lord et al., 2013; Inzitari et al., 2007). Whereas stride time loads onto the rhythm domain, and stride length variability loads onto the variability domain.

2.5 Statistical Analysis

All data collected from participants were entered into computerised files and analysed using the IBM SPSS© (version 21 and 22) statistical package (SPSS Software, Seattle, WA, USA). For each experiment, the data were tested for normality using Shapiro-Wilk tests. A small number of extreme outliers sitting at 3 times the interquartile range (3xIQR) were investigated and manually removed from analysis to avoid undue skew of the data. The 3xIQR rule in a normal distribution identifies cases that appear with a probability if less than 1%. Demographic characteristics and control measure data were compared between groups, where relevant, using independent t-tests and one-way analyses of variance (ANOVAs). Where a dual-task paradigm was employed, an additional variable of dual-task change (DTC) was calculated. The DTC is a percentage measure of interference. The DTC% was calculated by taking the difference in performance between single-task and dual-task conditions, dividing it by the single-task performance, and then multiplying this number by 100 (Bock, 2008): $DTC\% = \left(\frac{ST-DT}{ST}\right) * 100$. Using this formula when larger values indicate better performance (cognitive accuracy, gait speed and mean stride length) with the ST as a baseline, a positive DTC value indicates worse performance in the DT condition. However, when lower values indicate better performance (such as reaction times, mean stride time, stride time variability and stride length variability), a positive DTC value would mean performance was better in the DT condition. With these data, the formula was altered slightly: $DTC\% = \left(\frac{-(ST-DT)}{ST}\right) * 100$. Therefore, all positive DTC values indicate worse performance in the DT condition.

Group comparisons and within-group task comparisons were made using independent and paired-samples t-tests, and appropriate analyses of variance (ANOVAs). Appropriate post-hoc analyses were carried out where main effects were observed. A

significance level of 0.05 was set for all analyses initially, with a Bonferroni corrected alpha utilised where multiple t-tests were conducted to compare between or within groups. The Bonferroni correction divides the original alpha value (0.05) by the number of comparisons being tested, giving a more conservative cut-off value for determining statistical significance and reducing the increased risk of a Type I error. In addition to significance values, measures of effect size were also calculated.

2.6 Ethical Approval and Participant Recruitment

All experiments were carried out in accordance with the ethical standards of the American Psychological Association (APA) and the Declaration of Helsinki (World Medical Association, Inc). Ethical approval was obtained from Maynooth University Ethics Board for all experiments (see Appendices F-H). For Experiment 4, additional approval was granted from the Research Ethics Committee at Tallaght Hospital (see Appendix I).

A number of different population samples were recruited *ad hoc* for the experiments conducted in this thesis. Samples recruited for Experiments 1-3 consisted of healthy young adults, healthy community-dwelling older adults, and (otherwise healthy) community-dwelling idiopathic fallers. These participants were recruited from Maynooth University, the local Maynooth community and the towns surrounding Maynooth in Co. Kildare. Participants responded to notices and advertisements on campus, in local publications and on local radio, as well as announcements made on campus and at local community group meetings (e.g. active retirement groups, Maynooth University Mature Students society). For Experiment 4, persons who had experienced a stroke were recruited from the William Stokes Stroke Unit patient database at Tallaght Hospital, south Co. Dublin. Past patients were contacted by letter initially (including a patient information leaflet and consent form; see Appendix N), inviting them to take part in a study being

carried out by Maynooth University and the William Stokes stroke unit at Tallaght Hospital. A comparative healthy older adult control group was recruited for Experiment 4 from the surrounding south Co. Dublin area of the hospital, and also from the surrounding areas of Maynooth University in Co. Kildare.

In all cases, participants were informed that volunteers were being sought to take part in a study investigating the role of different brain processes in walking and falls, taking place at Maynooth University or Tallaght Hospital. Anyone who responded to the recruitment call was given verbal and/or written information regarding the nature of the study, what types of tasks and measures would be used, what participation would entail on their part, and the expected duration of their participation (approximately). Exclusion and inclusion criteria were screened via telephone prior to making an appointment to take part (see Table 2.2 for the inclusion and exclusion criteria for each sample).

Written consent was obtained before the time of participation, or on the day, before the experiment commenced (following prior verbal consent via telephone; see Appendices J-N for consent forms used for Chapters 3, 4, 5 and 6). Where EEG measures were utilised, participants were informed of the equipment, how it is applied, the procedure of EEG measurement, and a general summary of what it measures. Participants were also warned that due to the use of conductive gel on the scalp, they may need to wash their hair after taking part, and facilities to do so were provided at each testing site. SignaGel® is a highly conductive water-soluble gel that is bacteriostatic and sensitive on skin (non-irritating and non-gritty). However, a patch test was carried out on the wrist of each participant (to test for potential skin allergies) at least 20 minutes before it was applied to the scalp.

Participants were made aware that their data and results would be coded confidentially for anonymity, with all collected data stored separately to consent forms.

Furthermore, participants were informed that they could stop the experiment at any time, and could withdraw their participation or their data at any point without question or consequence. If a participant expressed concerns about their performance on any measures (e.g. memory and recall), they were advised to contact their medical care provider or general practitioner, and informed that none of the measures utilised in this research could be used for diagnostic purposes. A full debriefing was provided at the end of participation, with any and all queries and questions answered by the experimenter.

Table 2.2: ***Key inclusion and exclusion criteria for all experiment sample groups.***

Criteria	Healthy Young Adults (Y)	Healthy Older Adults (OA)	Patients post-Stroke (PPS)
Inclusion:	a) Age 18+ years; b) Independently mobile.	a) Age 55+ years; b) Ability to walk upright for at least 15m. c) Community dwelling	a) Aged 55+ years b) Ability to walk upright for at least 15m c) At least 6 months post-stroke/CVA
Exclusion:	a) Severe uncorrected sensory impairment b) History of psychological/neurological impairment c) Severe head trauma (with unconsciousness) d) Currently on psychoactive or balance-impairing medication e) History of epilepsy f) History of drug or alcohol problems g) Any relevant vestibular or musculoskeletal conditions h) Labyrinthectomy	a) Unable to walk 15m, with or without aid b) MMSE® score < 10 c) Dementia, or moderate-severe aphasia d) Severe uncorrected sensory impairment e) History of psychological/neurological impairment f) Severe head trauma (with unconsciousness) g) Currently on psychoactive or balance-impairing medication h) Unstable blood pressure/heart condition i) History of epilepsy j) History of drug or alcohol problems k) Lower limb amputation, recent joint replacement l) Other relevant vestibular or musculoskeletal conditions m) Labyrinthectomy	a) Unable to walk 15m, with or without aid b) Less than 6 months post stroke/CVA c) MMSE® score < 10 d) Unable to provide consent e) Severe hemiplegia f) Dementia, or moderate-severe aphasia; g) Severe uncorrected sensory impairment h) History of prior psychological/ neurological impairment i) Severe head trauma (with unconsciousness); j) Currently on psychoactive or balance-impairing medication; k) Unstable blood pressure/heart condition l) History of epilepsy m) History of drug or alcohol problems n) Lower limb amputation, recent joint replacement o) Other relevant vestibular or musculoskeletal conditions p) Labyrinthectomy

Chapter 3

Domain specific dual-task effects on gait performance over 5m and 15m, in healthy young adults.

Abstract

Dual-task studies are often used to examine the cognitive-motor link underlying gait control. Previous work has indicated a role for higher-level cognitive processes (namely executive functions) in gait control within young adults and those with a higher risk for falls (e.g. older adults). However, due to considerable methodological variability in the literature, it is not clear which specific executive processes (e.g. attention, working memory, inhibition) play a role, and if the length of the walkway (5m, 10m, 15m) used for testing has an impact on measuring dual-task interference. This chapter presents an experiment investigating the effects of different dual-tasks on gait performance in healthy young adults over two different walking distances (5m and 15m). Forty healthy young adults were recruited; 20 participants were allocated to the 5m distance group and 20 to the 15m distance group. Within each group, gait and cognitive performances were analysed during single-task and various dual-task conditions. The dual-tasks targeted simple divided attention and motor responding (Motor task), visuospatial processing (Clock task), executive working memory (2-back task) and executive attention and updating/working memory (Subtraction task). Results found that there were more changes in stride time (longer) and gait speed (slower) for the executive tasks, with the Subtraction task and Clock task exhibiting comparatively more interference on gait performance over a 15m walking distance. These findings help clarify the specific processes underlying cognitive-motor inference during dual-task walking.

3.1 Introduction

The ability to maintain stability while navigating various terrains and obstacles, attending to environmental information and distractions, all while processing sensory feedback, distinguishes gait control as a highly complex behaviour requiring cognitive flexibility and multidimensional processes (Hausdorff, Yogev, Springer, Simon, & Giladi, 2005; Szturm et al., 2013). Oftentimes, in everyday life, we carry out this complex behaviour while multitasking: when we walk while carrying multiple objects, or while talking or texting on a mobile phone. The long held assumption that walking is an automated motor function has been disregarded, with a growing body of evidence demonstrating a relationship between cognitive and motor processing in the brain while walking (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2008). For example, older adults and clinical samples (e.g. persons with dementia) who exhibit cognitive impairments also have an increased risk for falls (Al-Yahya et al., 2011; Muir, Gopaul, & Montero Odasso, 2012; Shaw, 2002). Research into this cognitive-motor link suggests that walking gait requires attention and is, at least in part, governed by top-down higher-level cognitive processes (Hausdorff et al., 2005).

The overlap of cognitive and motor processing during walking is often examined using the dual-task (DT) paradigm (Al-Yahya et al., 2011; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2008). In DT studies, participants walk while performing a secondary task, and the DT change or interference (mainly for gait performance) is assessed. Cognitive theories argue that these decrements in gait performance are a result of shared cognitive resources being redirected from gait control to the secondary task (central capacity-sharing model: Pashler & Johnston, 1998). The effect of a DT load should be measured in both directions (on cognitive and motor performance) as deterioriarion of performance in one task could indicate task prioritisation. However,

many studies in the past have focused solely on costs to gait performance (Al-Yahya et al., 2011).

A systematic review and meta-analysis of the cognitive-motor DT literature has shown that cadence, gait speed and stride length all decrease during dual-tasking, while stride time and stride time variability increase (Al-Yahya et al., 2011; Gomes et al., 2016). In particular, variability measures are considered to be indicators of gait control (i.e. stability and automaticity) in the DT literature (Allali, Kressig, Herrmann, & Beauchet, 2007; Hausdorff, Edelberg, Mitchell, Goldberger & Wei, 1997; Lassoe et al., 2008). However, the effects of DTs on variability measures is unclear in studies of young adults. A review from 2008 reported that during DT walking, young adults generally maintain gait variability dynamics equivalent to single-task (ST) walking (Yogev-Seligman et al., 2008). More recently, some studies report that variability increases during DT walking in healthy adults (Asai, Doi, Hirata, & Ando, 2013; Szturm et al., 2013), while others report that variability decreases (Wrightson, Ross & Smeeton, 2016), highlighting the complexity of this measure. Szturm et al. (2013) found that variability of temporal gait parameters generally increased, as cognitive performance decreased in young adults simultaneously performing a visuospatial cognitive task. However, Wrightson, Ross & Smeeton (2016) found that both a serial Subtraction task and 2-back working memory task were equivalent in significantly reducing stride time variability in healthy young adults (suggesting that participants prioritised cognitive performance, by redirecting cognitive resources away from the motor gait performance).

The most robust and commonly reported gait impairment during DT conditions is reduced gait speed (Al-Yahya et al., 2011; Gomes et al., 2016). Healthy young adults have been reported to generally walk slower when completing a secondary task, sometimes with concurrent decline in cognitive task performance (Yogev-Seligman et al.,

2008). When sufficient cognitive resources are taxed or impaired, a slower gait speed is likely a compensatory strategy for maintaning stability and avoiding falls, particularly when navigating challenging environments (Van Iersel, Ribbers, Munneke, Borm & Rikkert, 2007). Despite this evidence for speed change, a more recent systematic review and meta-analysis revealed that DT walking speed was not a better predictor of falls in older adults in comparison to ST walking speed (Menant, Schoene, Darofim & Lord, 2014). Yogev-Seligman et al. (2008) also reported that some DT studies show no effect of cognitive task on gait performance in healthy young adults, and argued that this may be due to participants being explicitly told to priortise the walking task or due to low cognitive task difficulty. Others have also shown that the type and complexity of both the walking and cognitive task, will affect DT performance costs in healthy young adults (Al-yahya et al., 2011; Beurskens & Bock, 2012; Patel, Lamar & Bhatt, 2014).

These mixed findings may be attributed to the large methodological variability in the DT literature, particularly regarding the choice of secondary cognitive task (e.g. memory recall tasks, motor tray carrying task, spontaneous speech, Stroop task: Al-Yahya et al., 2011; Beurskens & Bock, 2012). It is important to remember that cognition is not a unitary construct, but rather a complex system of multiple and varied processes, including sub-domains, which can often be targeted with many variations of tasks. The use of general cognitive tasks, or tasks that are not domain-specific, adds little to our understanding of the cognitive-motor link and makes comparison across studies difficult (Worden, Mendes, Singh & Vallis, in press, 2016). Furthermore, this also has ramifications for translating this knowledge to the clinical setting (for the effective use of DTs as a screening and/or intervention tool). However, recent systematic reviews (Al-Yahya et al., 2011; Chu, Tang, Peng & Chen 2013; Gomes et al., 2016; Hsu, Nagamatsu, Davis & Liu-Ambrose, 2012) and other studies seem to indicate that higher-level

executive function (EF) processes may be the key contributor to gait control, as tasks of executive control affect gait more than simple divided attention or discrimination tasks (Beurskens & Bock, 2012; Hausdorff et al., 2005). For example, performance on EF measures has been shown to correlate with gait speed in both ST and DT conditions, as well as to predict falls in older adults (Killane et al., 2014; Mirelman et al., 2012). However, executive control can also be subdivided into multiple processes involving various cortical inputs (Yogev-Seligman et al., 2008). These processes include goal-directed decision making, planning, purposive action, action monitoring/information updating, and inhibition. Many previous studies have often employed only one executive DT, or have failed to include non-executive simple attention demanding tasks for relative comparisons (van Iersel, Kessels, Bloem, Verbeek, & Olde Rikkert, 2008; Szturm et al., 2013).

To gain a better understanding of the specific higher-level processes underlying gait control, this study compared the effects of multiple secondary tasks, within the same testing session, on DT gait in healthy young adults. A Subtraction task and an n-back task (2-back) were utilised as they are commonly used in the DT literature, and are known to target executive processes. The Subtraction task taxes higher-level executive attention, information updating and working memory (Baetens et al., 2012; Mertens et al., 2006; Moneterro-Odasso et al., 2009; Srygley, Mielman, Herman, Giladi & Hausdorff, 2009), while the 2-back task targets executive working memory processing (Owen, McMillan, Laird & Bullmore, 2005). We also used the Clock task, which requires visualisation and visuospatial executive processes (adapted from Haggard et al., 2000). In addition, we included a simple motor response task as a control DT, allowing relative comparisons between tasks targeting higher-level executive processes, and simple divided attention for tone discrimination and motor responding. We also recorded cognitive responses in both

the ST and DT condition, to assess the DT effect on both gait and cognitive performance (which has not always been the case in previous literature: Al-Yahya et al., 2011).

We also wished to investigate the effect of walkway length on DT effects. While some studies have looked at the effect of different walking speeds, walkway width, and treadmill or over ground walking on DT performances (Beurskens & Bock, 2012; Patel, Lamar & Bhatt, 2014; Wrightson, Ross, Smeeton, 2015), few have examined the effect of the length of the walkway on DT interference. Previous studies have shown that walking distance can affect spatiotemporal parameters of gait in both young and older adults during normal (ST) walking (Najafi, Helbostad, Moe-Nilssen, Zijlstra & Aminian, 2009; Najafi, Khan & Wrobel, 2011). Specifically, these authors show that young adults walk faster over longer distances (7m vs. 14m, and 14m vs. 20m). Other laboratory studies have suggested that speed and measures of variability are only valid at longer distances of 10m and 15m (Montero-Odasso, 2006; Hollman et al., 2010), as longer distances provide more data points and step cycles, allowing for more consistent calculations of variability and test-retest reliability (Koenig, Singh, von Beckerath & Taylor, 2013; Monaghan, Delahunt & Caulfield, 2007).

However, more recently there has been a focus on examining walking gait during daily living, and these studies have shown that walking bouts are short, with low numbers of sequential steps (Orendurff, Schoen, Bernatz, Segal & Klute, 2008). Furthermore, we are more likely to walk while conducting a secondary task over a short distance in the home. Clinical gait assessments at normal pace are also mostly conducted over a short distance (4m) for predicting adverse outcomes (Abellan van Kan et al., 2009). Here we compared DT changes over two different walkway distances with one group of young adults walking a 5m walkway, and another group walking over a 15m walkway.

3.1.1 Aims and Hypotheses

It is necessary to understand the cognitive-motor interference of different DTs in young healthy adults first, so that we may make comparisons to older adults and other clinical samples at a higher risk of falling. This will help us understand how gait control changes with ageing and impairment. The first aim is to assess the relative role of different higher-level cognitive processes by directly comparing the DT effects of explicitly different executive domains and attention-demanding tasks. The second aim is to identify if DT effects are different when measured over a 5m and 15m walkway distance. The role of each cognitive process will be determined by the amount of interference it has on walking gait and cognitive performance under DT conditions (relative to baseline ST performance). Given the healthy and capable nature of this sample (without fall-risk), it is hypothesised that overall, there will be limited impairments in gait while conducting the secondary tasks. We predict that participants will adopt a more stable gait to cope with the demands of the Clock, Subtraction and 2-back tasks. Therefore, we expect to see a slower gait speed and decreased variability while dual-tasking (in line with the work by Wrightson et al., 2016). By contrast, we expect very few changes (or none at all) in gait during the Motor DT. We predict that these healthy young adults will have adequate cognitive resources for maintaining cognitive performances while walking, so we do not expect cognitive performance to deteriorate from ST to DT conditions. We also predict that gait parameters will be different in the 5m and 15m walkway, as the 15m walkways will allow for a longer period of steady state walking (more gait cycles). However, we do not expect any differences in cognitive interference between the 5m and 15m groups.

3.2 Methods

3.2.1 Participants

A sample of 40 healthy young adults was recruited from the student population at Maynooth University, and split into two groups of 20 participants. One group completed the experiment protocol with a 5m walkway (9 male; age range 20-32 years; mean age 24.20 years) and the other group with a 15m walkway (8 male; age range 18-27 years; mean age 21.95 years). We did not use one group to complete the protocol over the 2 distances as there would be significant repetition of cognitive tasks in both the single and dual-task condition, which would cause practice effects. All participants gave written informed consent (see Appendix F), and reported that they were in good health, with no known conditions or impairments which may affect their walking or balance. This study was approved by the NUI Maynooth University Ethics Board, and conducted in accordance with the Code of Ethics of the World Medical Association and the ethical standards of the APA.

3.2.2 Gait Assessment

A straight, wide, well-lit, and obstacle-free walkway was mapped out with floor markings at beginning and end for both distances. The walkway was measured at 5m for one group (5m group) and 15m for the other (15m group). Kinematic data were recorded from two SHIMMER™ wireless sensors attached to the left and right shank, which were programmed to record data for 45s for the 5m group and 60s for the 15m group: these times were long enough for walking trials to be completed in each case, before the sensors stopped transmitting. All participants made 4 passes of the walkway in each condition. Spatial and temporal gait parameters were extracted from the data using an event-detection algorithm (see Chapter 2, section 2.4) that excluded initial and turning small

steps at each end of the walkway. Gait speed (m/s), stride time (s), stride time variability (%), stride length (m) and stride length variability (%) were analysed for all walking trials.

3.2.3 Dual-Tasks

Four tasks were employed for the DT condition. Three of these tasks were auditory stimulus-response tasks generated in E-Prime (Clock task, Motor task and n-back task conditions). These E-Prime tasks were presented on a Dell Latitude 2.1GHz Intel Pentium Processor laptop, with Dell external USB plug-in speakers. These tasks ran for 45s for the 5m group and 60s for the 15m group. The fourth cognitive task was a numerical Subtraction task recorded with pen and paper. All cognitive DTs were also carried out while seated (the ST condition) in order to investigate the bidirectional effects of dual-tasking on gait and cognitive performances.

3.2.3.1 Motor task

A motor response task was used as a simple attention-demanding task that should not tax working memory or EF processing (to be used as a relative control task for more demanding DTs). In this task, 2 different auditory tones (16-Bit WAV file; 1411kbps; 1000ms long) were presented via the speakers. Participants were instructed to respond quickly to each tone by clicking the left or right button of a wireless mouse (held in their dominant hand). A sample of the two tones was played before the task commenced, and participants were told which mouse button (left or right) was paired with each tone. Stimuli were presented in a randomized order for both the DT and ST condition, at randomly varied delay intervals (500ms, 750ms or 1000ms), with a 3000ms response window from stimulus onset. Response accuracy and reaction times were automatically logged in E-Prime.

3.2.3.2 Clock task

The Clock task is a visuospatial task which taxes executive control and working memory (adapted from Haggard, Cockburn, Cock, Fordham, & Wade, 2000). Auditory stimuli were presented via the speakers, which consisted of a female voice reading a series of times: e.g. “one-oh-five”; “three-fifteen”; “seven-forty”. The stimuli were 16-Bit WAV files, 1000ms long, with a 1411kbps bit rate. There was a 3000ms response window from stimulus onset, and a 500ms stimulus interval. Participants were required to visualise a round-faced clock as each time was announced, and visualise where the hour and minute hands of the clock would be for that particular time. If both clock hands were on the same left or right vertically bisected half of the clock (between 1 and 5, or 7 and 11), participants were required to verbally respond “YES” (e.g.: 1:15). Participants were required to respond “NO” if the clock hands were on opposite sides of the clock (e.g.: 3:45). Times bisecting the clock (6 and 12 o’clock and 0 and 30 minutes) were not included in the stimuli. There was an equal chance of either a “YES” or “NO” trial being presented each time. Stimuli were randomised each time the task was run so that the order varied for participants, and across the DT and seated ST conditions. Participant responses were logged by the experimenter on the laptop to measure accuracy.

3.2.3.3 n-back task

An auditory 2-back task was used to also tax higher-level executive control working memory processing (Owen et al., 2005). A series of nouns (e.g.: “channel”, “errand”, “jacket”, “garden”), read by a female voice, were played one at a time with a 100ms inter-stimulus delay, from the speakers (Toronto Noun Pool; 16-Bit WAV file; 1411kbps bit rate; 1500ms response window). Some words were repeated after a 1-word interval in the

sequence: e.g. “dog”–“table”–“pen”–“table”. Participants were instructed to listen to the nouns and to respond by saying the word “MATCH” when they heard a word that was a repeat (or match) of the word presented two trials previously. In this way, the task required participants to hold the previous 2 words in their memory (2-back), while listening and deciding whether or not to respond to the currently played word. Twenty-seven percent of the trials were target trials, and responses were logged on the computer by the experimenter. The stimulus sequence was different for ST and DT conditions to control for learning effects.

3.2.3.4 Subtraction task

The serial Subtraction task is a commonly used as a general cognitive load task in studies of gait, but is argued to specifically tax working memory and information updating (Mertens, Gagnon, Coulombe, & Messier, 2006). Participants were instructed to start at the number 100 and subtract in intervals of 3, aloud, for 45s in the 5m group, and 60s in the 15m group (e.g. 100, 97, 94...). Participants were told to restart the task at 100 if they counted to 0 before the 45 or 60 seconds had elapsed. Accuracy was measured, and a correct response rate (CRR) was calculated as number of correct responses divided by time (45s and 60s respectively).

3.2.4 Procedure

Informed written consent was obtained from each participant at the start of the session, before commencing any testing, with a full verbal debriefing provided by the experimenter upon completion. In total, participants conducted 2 separate walking ST trials, 4 cognitive DTs and 4 cognitive STs in each distance group. Participants completed one ST walking trial at the beginning, followed by the cognitive ST and DT conditions,

and finally the second ST walking trial. In order to minimize the effects of learning, the cognitive ST and DT conditions were counterbalanced across participants (50% completed the sit-down cognitive tasks first). See Figure 3.1. Within the DT condition, the order of the cognitive DTs was also varied. All tasks were completed in one session lasting approximately 45mins in total (with shorts breaks offered to participants between tasks).

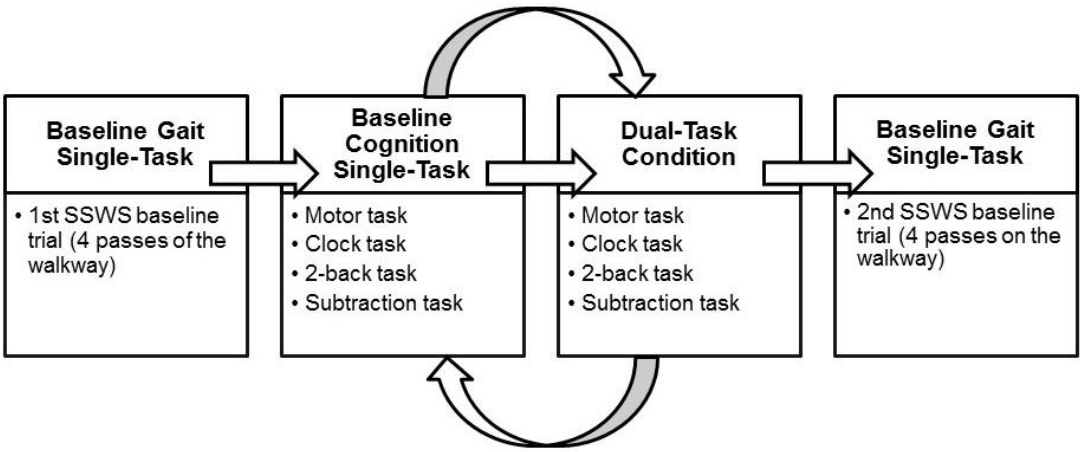

Figure 3.1 *Experiment procedure of tasks and conditions, ordered from left to right.*

Participants were instructed to walk the length of the walkway 4 times for each walking ST and DT trial, with 180° turns after each length of the pathway. Participants were asked to start walking with their right leg, to walk at what they considered to be their normal everyday pace (self-selected walking speed: SSWS), and asked to stand still upon completion of each trial (until the sensors stopped transmitting). Two ST walking trials were conducted so that an average of both could be taken as a measure of usual pace steady-state gait. All cognitive DTs were also performed while seated in a cognitive ST condition. Participants were not instructed to prioritise walking or the cognitive performance in the DT condition. The DT change (DTC) was calculated to assess the

effect of dual-tasking on both cognitive and gait performances (percentage change from ST to DT trials: see Chapter 2, section 2.5).

3.2.5 Statistical analysis

Cognitive accuracy, correct response rate and reaction time values (where applicable), spatiotemporal gait values, and the cognitive and motor DTC values were analysed. The DTC values reflect the relative change in gait and cognitive scores from baseline ST trials to DT trials. Positive values indicate worse performance on DT trials, and negative values indicate better performance on DT trials (see Chapter 2, section 2.5). A small number of extreme outlying points falling outside 3 times the interquartile range were removed from the data set.

One-way ANOVAs were used to analyse the effect of the different cognitive DT conditions on the various gait measures (1x5 repeated measures ANOVA). Paired samples t-tests were used to investigate changes in cognitive performance between the sitting ST and walking DT conditions. Mixed factorial ANOVAs were also used to examine the effect of walkway distance (between factor: 5m vs 15m) and effect of task type (within factor) on the relative change DTC values for cognitive and motor performances (2x4 ANOVA). Homogeneity of variances was examined using Levene's tests, and the Greenhouse-Geisser correction was employed where the assumption of sphericity was violated. Bonferroni-corrected alpha values were used to avoid a Type 1 error, where multiple comparisons were made.

3.3 Results

3.3.1 Group comparisons

Although the mean age of the 5m and 15m groups were similar (5m group: *M* = 24.20, *SEM* = 0.78, range: 20-32 years; 15m group: *M* = 21.95, *SEM* = 0.57, range: 18-27 years), there was a statistically significant difference in these means when compared using an independent t-test: $t(38) = 2.35$, $p = .02$. When compared on baseline ST walking, the two distance groups also had significantly different walking speeds and mean stride times [speed: $t(38) = -4.57$, $p < .001$; stride time: $t(38) = 5.55$, $p < .001$]. Gait speed and stride time were significantly slower and longer, respectively, in the 5m walkway group (speed: *M* = 1.02, *SEM* = 0.03; stride time: *M* =1.07, *SEM* = 0.01), compared to the 15m walkway group (speed: *M* = 1.17, *SEM* = 0.02; stride time: *M* = 0.96, *SEM* = 0.01). Baseline cognitive performances in the seated ST condition were also compared across groups, which showed a significant difference between the groups on Motor reaction times (RT) and Subtraction task accuracy: [motor: $t(38) = 6.19$, $p < .001$; Subtraction: $t(22.08) = 2.65$, $p = .011$]. Motor RTs were faster for the 15m group (*M* = 599.09, *SEM* = 22.47 vs. 5m group: *M* =904.54, *SEM* = 43.95), and accuracy was higher in the 5m group on the Subtraction task (*M* =99.32, *SEM* = 0.38) compared to the 15m group (*M* =95.48, *SEM* = 1.33). Due to these differences, direct comparisons were not made between the groups on measures of DT gait or cognitive function (walkway distance was not used as a between-groups factor). However, the groups were compared on DTC values which represent relative change from their respective baseline performances.

3.3.2 Gait Analysis

The mean (*M*) and standard error of the mean (*SEM*) values for all gait variables across the walking conditions are shown in Table 3.1 for the 5m and 15m groups. There was a

significant main effect of DT task-type on gait speed and mean stride time in both the 5m [speed: $F(4, 72) = 3.01$, $p = 0.024$, $\eta 2 = 0.143$; stride time: : $F(2.033, 38.63) = 11.02$, $p < 0.001$, $\eta 2 = 0.367$] and 15m group [speed: $F(4, 76) = 8.01$, $p < 0.001$, $\eta 2 = 0.297$; stride time: $F(2.57, 48.75) = 20.93$, $p < 0.001$, $\eta 2 = 0.524$]. However, there were no changes in stride time variability [5m group: $F(4, 76) = 1.66$, $p = 1.69$, $\eta 2 = 0.66$; 15m group: $F(4, 76) = 0.66$, $p = .621$, $\eta 2 = 0.034$], mean stride length [5m group: $F(4, 76) = .73$, $p = 0.57$, $\eta 2 = 0.037$; 15m group: $F(4, 76) = 0.77$, $p = .55$, $\eta 2 = 0.039$] or stride length variability [5m group: $F(4, 76) = 0.85$, $p = 0.5$, $\eta 2 = 0.043$; 15m group: $F(4, 76) = 1.26$, $p = .292$, $\eta 2 = 0.062$].

Follow-up analyses of main effects were conducted for speed and stride time. In the 5m group, gait speed was significantly slower ($p = .048$) on the 2-back DT ($M = 0.93$, $SEM = 0.02$) compared to baseline ST walking ($M = 1.02$, $SEM = 0.03$). See Figure 3.2. Stride time was also significantly longer than baseline ($M = 1.07$, $SEM = 0.01$) on all DT trials (all $p < .007$): Motor DT: $M = 1.17$, $SEM = 0.02$; Clock DT: $M = 1.19$, $SEM = 0.03$; Subtraction DT: $M = 1.23$, $SEM = 0.05$; 2-back DT: $M = 1.17$, $SEM = 0.03$ (see Figure 3.3).

However, in the 15m group, participants walked significantly slower than baseline ($M = 1.17$, $SEM = 0.02$) on the Clock task ($M = 1.11$, $SEM = 0.02$, $p = .009$) and Subtraction task ($M = 1.07$, $SEM = 0.02$, $p < .001$), as well as the 2-back task ($M = 1.10$, $SEM = 0.03$, $p = .019$). See Figure 3.2. Similarly to the 5m group, the 15m group also had longer stride times (all $p < .001$) than baseline ($M = 0.96$, $SEM = 0.01$) on all DTs: Motor DT ($M = 0.99$, $SEM = 0.02$), Clock DT ($M = 1.01$, $SEM = 0.02$), Subtraction DT ($M = 1.03$, $SEM = 0.02$) and 2-back task ($M = 1.00$, $SEM = 0.02$). However, stride time on the Clock task and the Subtraction task were also significantly greater (all $p < .038$) than the Motor task, as well as the ST, in the 15m group (see Figure 3.3).

Table 3.2. *Mean (and standard error of the mean) values for speed, stride time, CV stride time (variability), stride length and CV stride length (variability) values for each DT (DT) conditions in the 5m and 15m groups.*

5m Group

Gait Measure	ST	Motor DT	2-back DT	Clock DT	Subtraction DT
Speed (m/s)	1.02 (0.03)	0.98 (0.03)	0.93 (0.02)	0.94 (0.03)	0.91 (0.03)
Stride Time (s)	1.07 (0.01)	1.17 (0.02)	1.17 (0.03)	1.19 (0.03)	1.23 (0.05)
CV Stride Time (%)	9.15 (0.77)	10.02 (1.15)	8.42 (0.66)	9.43 (0.91)	11.70 (1.34)
Stride Length (m)	1.08 (0.02)	1.14 (0.02)	1.10 (0.02)	1.10 (0.03)	1.10 (0.02)
CV Stride Length (%)	51.19 (1.86)	46.57 (1.95)	48.82 (1.53)	49.05 (2.18)	47.75 (1.75)

15m Group

Gait Measure	ST	Motor DT	2-back DT	Clock DT	Subtraction DT
Speed (m/s)	1.17 (0.02)	1.13 (0.02)	1.10 (0.03)	1.11 (0.02)	1.07 (0.02)
Stride Time (s)	0.96 (0.01)	0.99 (0.02)	1.00 (0.02)	1.01 (0.02)	1.03 (0.02)
CV Stride Time (%)	6.98 (0.28)	6.76 (0.28)	6.73 (0.34)	6.71 (0.30)	7.08 (0.38)
Stride Length (m)	1.11 (0.01)	1.11 (0.01)	1.10 (0.02)	1.11 (0.01)	1.09 (0.01)
CV Stride Length (%)	47.77 (0.82)	49.86 (1.26)	49.44 (1.18)	47.22 (0.95)	49.45 (0.95)

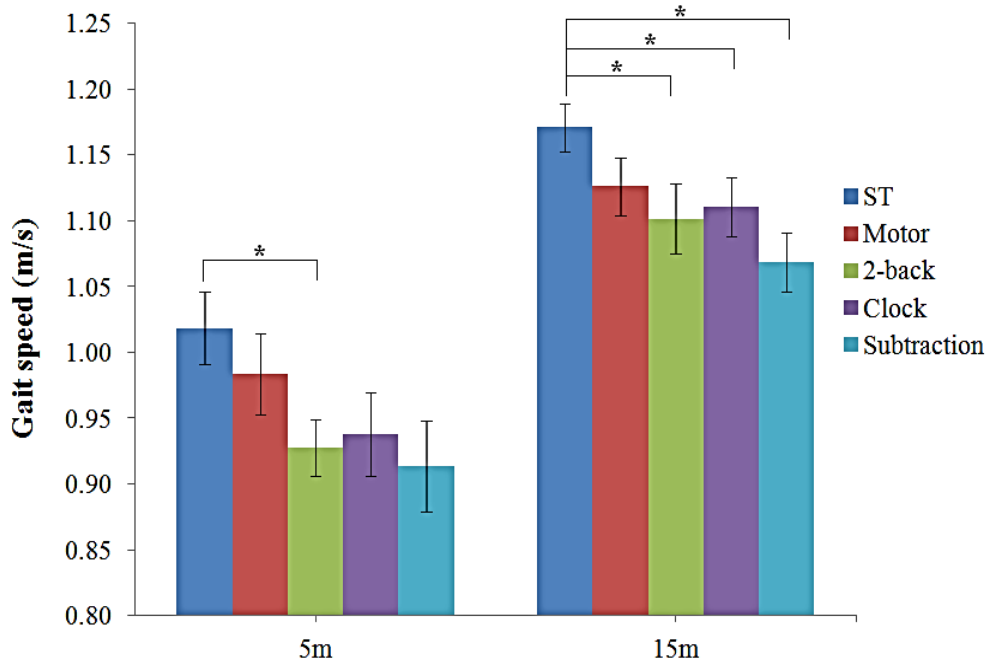

Figure 3.2. *Mean gait speed (m/s: +/- SEM) across single (ST) and DT (DT) conditions in both the 5m and 15m group (*indicates significance at the Bonferroni corrected alpha).*

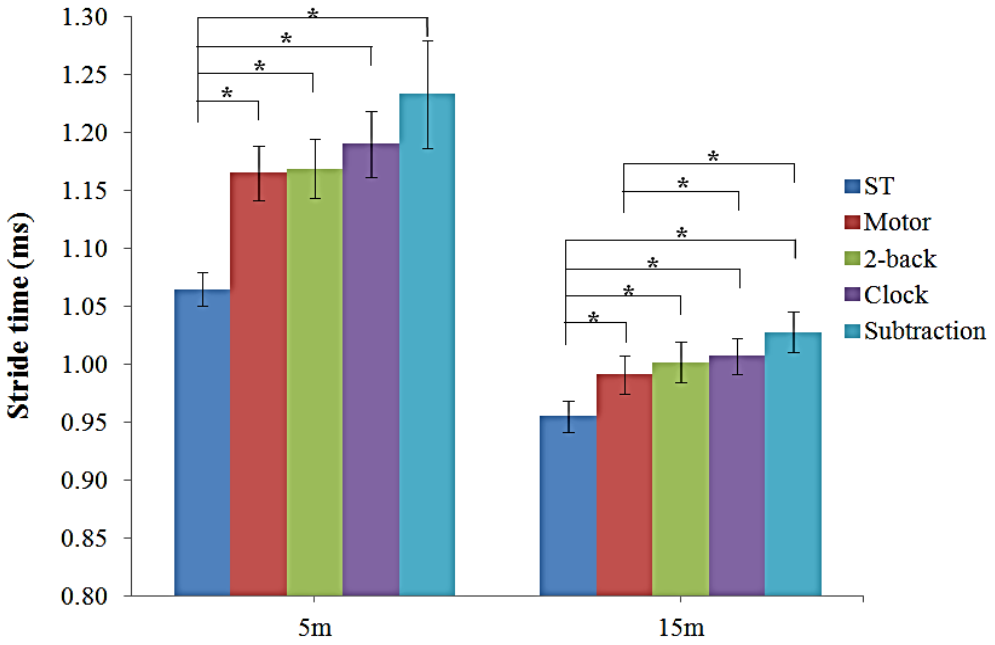

Figure 3.3. *Mean stride time (ms: +/- SEM) for single (ST) and DT (DT) conditions in both the 5m and 15m groups (* indicates significance at the Bonferroni corrected alpha).*

3.3.2.1 Gait DTC

The mean (and SEM) gait DTC values for each task type are presented in Table 3.2. DTC values (relative change from ST to DT) for each of the gait variables were compared between the 5m and 15m group and across the 4 DTs (2x4 mixed factorial ANOVA).

3.3.2.1.1 Speed DTC

There was a significant main effect of task type on speed DTC [$F(3, 111) = 3.21$, $p = .026$, $\eta p^2 = 0.08$], but no main effect for walkway distance [$F(1, 37) = 0.76$, $p = .390$, $\eta p^2 = 0.02$] and no significant interaction between task type and distance [$F(3, 111) = 0.34$, $p = .795$, $\eta p^2 = 0.009$]. See Figure 3.4. Follow up within-group comparisons revealed no significant main effect for task type on speed DTC in the 5m group: $F(3, 54) = 1.44$, $p = .243$, $\eta p^2 = 0.074$. Conversely, in the 15m group, speed DTC on the Subtraction task ($M = 8.69$, $SEM = 1.47$) was significantly greater ($p = .038$) than on the Motor task ($M = 3.74$, $SEM = 1.41$): $F(3, 57) = 3.03$, $p = .037$, $\eta p^2 = 0.137$].

Table 3.2. *Motor DT change (DTC %) values for speed, stride time, CV stride time (variability), stride length and CV stride length (variability) values for each DT (DT) conditions in the 5m and 15m group.*

5m Group

Gait DTC	Motor DT	2-back DT	Clock DT	Subtraction DT
Speed DTC%	2.21 (3.73)	7.62 (2.09)	6.77 (3.84)	9.63 (3.27)
Stride Time DTC%	9.63 (1.85)	9.88 (1.86)	12.03 (2.51)	15.77 (3.91)
CV Stride Time DTC%	8.76 (12.97)	-5.89 (8.18)	10.44 (10.70)	35.86 (16.27)
Stride Length DTC%	-6.58 (3.53)	-3.02 (2.79)	-3.51 (3.66)	-3.39 (3.69)
CV Stride Length DTC%	-7.08 (4.84)	-2.28 (4.58)	-2.14 (5.13)	-4.28 (4.87)

15m Group

Gait DTC	Motor DT	2-back DT	Clock DT	Subtraction DT
Speed DTC%	3.74 (1.41)	5.97 (1.65)	5.10 (1.32)	8.69 (1.47)
Stride Time DTC%	3.76 (0.77)	4.85 (0.80)	5.48 (0.75)	7.67 (1.20)
CV Stride Time DTC%	-1.92 (3.96)	-2.96 (3.91)	-3.30 (2.64)	1.74 (3.34)
Stride Length DTC%	0.18 (1.33)	1.48 (1.55)	-0.06 (1.32)	1.83 (1.37)
CV Stride Length DTC%	4.88 (2.98)	3.94 (2.79)	-0.76 (2.30)	4.35 (3.16)

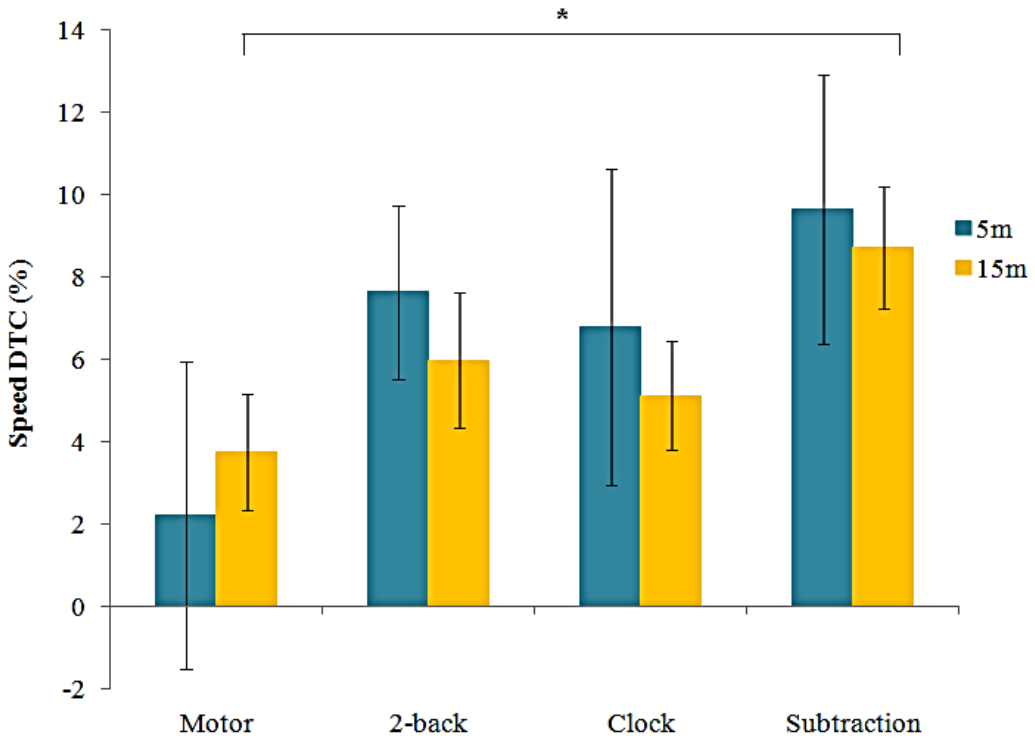

Figure 3.4. *Mean (+/- SEM) dual-task change (DTC) in speed for each dual-task in both the 5m and 15m groups (* indicates significance at the Bonferroni corrected alpha).Larger values indicate more relative change in speed (speed slowed most for the Subtraction dual-task).*

3.3.2.1.2 Stride time DTC

Similarly to speed DTC, there was a significant main effect of task type on stride time DTC [$F(1.79, 68.10) = 6.30$, $p = .004$, $\eta p^2 = 0.142$]. There was also a main effect for distance [$F(1, 38) = 7.33$, $p = .01$, $\eta p^2 = 0.162$], but no interaction effect [$F(1.79, 68.10) = 5.37$, $p = .568$, $\eta p^2 = 0.014$]. The change in mean stride time on the motor task was significantly greater in the 5m walkway group ($M = 9.63$, $SEM = 1.85$) than the 15m ($M = 3.76$, $SEM = 0.77$) walkway group: $t(25.33) = 2.94$, $p = .007$). Within the 5m group there were no main differences between task type [$F(1.78, 33.84) = 2.88$, $p = .076$, $\eta p^2 = 0.132$]. For the 15m group, the stride time DTC was significantly greater on the Clock task ($M = 5.48$, $SEM = 0.75$, $p = .02$) and Subtraction task ($M = 7.67$, $SEM = 1.20$, p

= .006) in comparison to the Motor task (M = 3.76, SEM = 0.77): F(1.80, 34.11) = 7.71, p = .002, ηp^2 = 0.289 (see Figure 3.5).

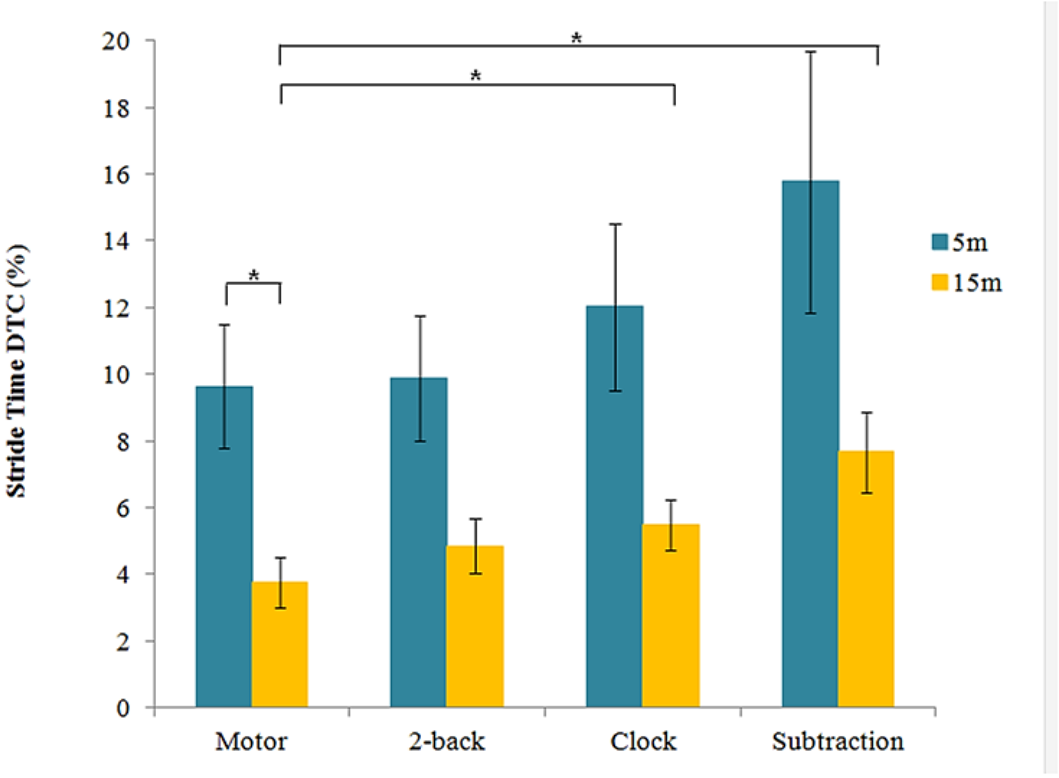

Figure 3.5. *Mean (+/- SEM) dual-task change (DTC) in stride time for each dual-task in both the 5m and 15m groups (* indicates significance at the Bonferroni corrected alpha). Larger values indicate more relative change in stride time (stride time increased the most for the Subtraction dual-task).*

3.3.2.1.3 Other gait variable DTC

There was no significant main effect for task type [F(2.66, 95.90) = 2.51, p = .70, ηp^2 = 0.065] or distance [F(1, 36) = 1.88, p = .179, ηp^2 = 0.05] on CV stride time DTC. There was also no interaction effect [F(2.66, 95.90) = 1.44, p = .237, ηp^2 = 0.039]. For stride length DTC, there was no significant interaction between task type and distance [F(3, 114) = 0.30, p = .829, ηp^2 = 0.008], and no main effect for task type [F(3, 114) = 0.80, p = .496, ηp^2 = 0.021], or group [F(1, 38) = 2.82, p = .101, ηp^2 = 0.069]. There was also no significant main effect for task type [F(3, 114) = 0.23, p = .877, ηp^2 = 0.006] or

distance [$F(1, 38) = 2.90$, $p = .097$, $\eta p^2 = 0.071$], on CV stride length DTC, and no interaction effect [$F(3, 114) = 1.03$, $p = .383$, $\eta p^2 = 0.026$].

3.3.3 Cognitive Analysis

The mean (and SEM) reaction time (RT) scores for the Motor task, and mean (and SEM) accuracy scores for the 2-back and Clock task, and CRR for the Subtraction task are shown in Table 3.4. Within group comparisons revealed no significant differences between ST and DT cognitive performances in the 5m group on the motor [$t(19) = -2.55$, $p = .02$], Clock [$t(19) = -0.05$, $p = .96$] or 2-back task [$t(17) = 0.00$, $p = 1.00$]. However, there was a significant decrease in Subtraction task performance from the ST ($M = 0.61$, $SEM = 0.04$) to the DT ($M = 0.52$, $SEM = 0.04$) condition: $t(19) = 3.23$, $p = .004$. In the 15m group, there was a significant difference between ST and DT performance for the Motor task [$t(18) = -5.57$, $p < .001$] and 2-back task [$t(16) = 2.80$, $p = .013$]. See Figure 3.6. Motor task reaction times were slower on the DT condition ($M = 653.99$, $SEM = 24.49$) than the ST ($M = 599.09$, $SEM = 22.47$). Accuracy on the 2-back task was also poorer on the DT ($M = 93.12$, $SEM = 1.58$) compared to the ST ($M = 98.94$, $SEM = 0.52$).

3.3.3.1 Cognitive DTC

Analysis of cognitive DTC values revealed no significant main effect for task type [$F(1.42, 51.20) = 2.40$, $p = .116$, $\eta p^2 = 0.063$], or distance [$F(1, 36) = 0.23$, $p = .638$, $\eta p^2 = 0.006$]. There was also no interaction effect [$F(1.42, 51.20) = 0.94$, $p = .369$, $\eta p^2 = 0.025$]. See Table 3.4 for *M* and *SEM* DTC (%) values.

Table 3.3. *Mean (and SEM) DT performance values (RT and ACC) for each task in single-task (ST) condition and DT (DT) condition and DT change relative change values (DTC%) for each, in the 5m and 15m group.*

	5m Group			15m Group		
Task	ST	DT	DTC%	ST	DT	DTC%
Motor RT (ms)	904.54 (43.95)	975.40 (37.79)	9.71 (3.26)	599.09 (22.47)	653.99 (24.49)	10.22 (1.75)
2-back ACC (%)	98.80 (0.59)	98.32 (0.71)	0.80 (1.49)	98.94 (0.52)	93.12 (1.58)	2.56 (1.39)
Clock ACC (%)	69.00 (6.42)	69.33 (5.08)	-9.74 (15.62)	77.82 (5.01)	78.87 (4.74)	-5.63 (8.16)
Subtraction CRR	0.61 (0.04)	0.52 (0.44)	14.40 (4.72)	0.50 (0.05)	0.51 (0.06)	-2.86 (5.81)

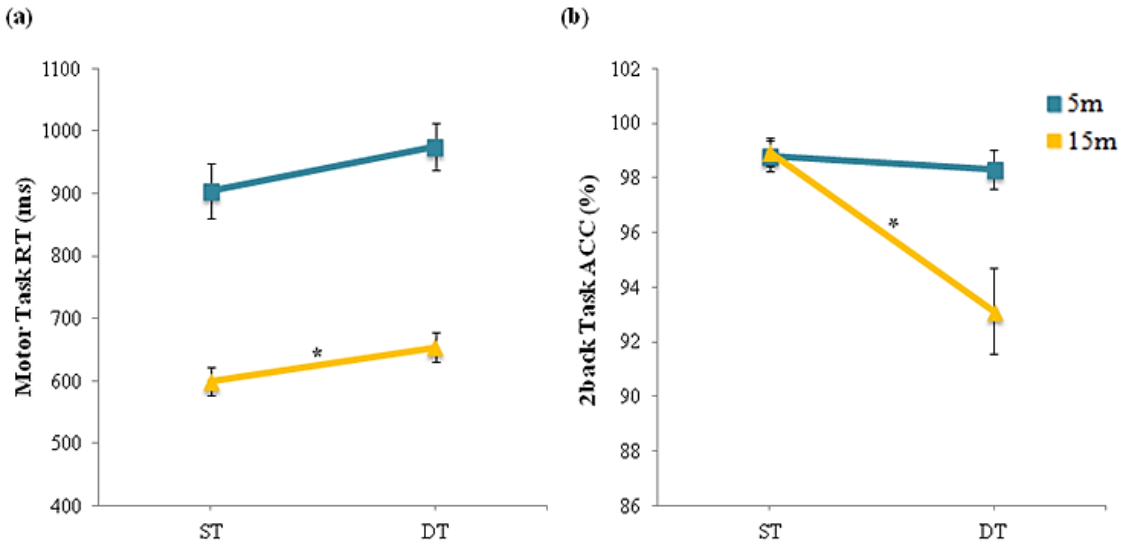

Figure 3.6. *Differences between single-task (ST) and DT (DT) for; a) Motor task reaction times (RT) in ms (+/- SEM); and b) 2-back task percentage accuracy (ACC: %: +/- SEM), in both the 5m and 15m group (* $p \leq 0.13$).*

3.4 Discussion

This experiment examined walking gait and cognitive performances under ST and DT conditions in healthy young adults, across a 5m and 15m walkway distance. The main aims were; 1) to compare the relative effects of varied secondary tasks (executive and non-executive) on DT walking gait; and 2) to examine if there are differences in gait DTC or cognitive DTC between a short (5m) and longer (15m) walkway distance.

There were no changes in stride length or measures of variability (CV stride time/length) from ST to DT for any secondary task over the 5m or 15m walkways. This is in contrast to our predictions that variability would decrease to support a more secure gait during DT walking (Wrightson et al., 2016). However, as previously mentioned, the complexity of gait variability measures is evident in the literature with mixed patterns of changes (increasing or decreasing), with some authors reporting no variability changes in healthy young adults (Al-Yahya et al., 2011; Yogev-Seligman et al., 2008). This may be due to the very capable nature of a healthy young adult sample, whereby changes in variability are not necessary to maintain a steady gait while dual-tasking.

However, there were significant reductions in speed and stride time while dual-tasking in over both walkway distances. The Motor task elicited a longer stride time over both the 5m and 15m walkway distance, with participants in the 5m group also showing slower reaction times on the Motor task, compared to ST baseline performances. Perhaps the slower reaction times on the 5m walk may be due to a shorter walkway between turn points, requiring more frequent adjustments to the walking task (step length and speed entering and leaving turns) compared to the 15m walkway group. However, no change was observed in gait speed overall. Therefore, the attentional demands of this basic Motor response task were enough to alter mean stride time, but not mean speed or the other characteristics of the DT gait. Perhaps participant response times were slower due to

resources being directed away from responding on the task to maintaining gait speed. However, as response times were not recorded for the EF tasks (only accuracy), we cannot make comparisons across tasks (there may have been changes in RT on these other DTs also). The limited stride time changes while conducting the Motor task may indicate that the attentional resources and motor function processes required for this task are not primarily essential to the control of gait. In this instance, the Motor task can act as a "control" task, allowing us to compare lower-level attention/discrimination processes and motor response functions–needed for most secondary tasks in the literature–to the additional, specifically higher-level executive processes taxed in the other three tasks. This is a strength of the current study design, allowing us to addresses the problem of methodological variability regarding the use of secondary tasks in the DT literature (Al-Yahya et al., 2011).

The EF tasks elicited more changes in gait performance than the Motor task, as predicted. The 5m and 15m groups both showed slower stride times for the Clock task, Subtraction task and 2-back task during DT walking (as for the Motor task). Additionally, the 15m group also had slower gait speeds on all executive tasks in comparison to the Motor response task. Overall gait speed was also slower than baseline for the 15m group on all tasks (and slower for the 2-back over 5m) during DT walking. This change in speed, with the related longer stride time, despite the maintenance of variability and stride length, might suggest that these gait changes do not necessarily reflect impairment. Rather, this could indicate that participants may have adopted a more stable and secure gait (slower speed and step times) to compensate for their divided attention, and the increased taxation of EF processes/resources (Beauchet et al., 2009; Van Iersel et al., 2007). This is in line with our predictions that there would only be minor changes to gait while dual-tasking. The maintenance of cognitive performance on the Clock and Subtraction tasks suggests

that participants prioritised cognitive performance over walking (without instruction to do so), or that these tasks were not challenging enough to affect both gait and cognitive performance in this young adult sample. Interestingly, accuracy on the 2-back task did deteriorate in the DT condition for the 15m group, in addition to the gait changes in speed and stride time. These bidirectional effects suggests that the underlying faculty of working memory was necessary for both the cognitive task completion and walking task performance, indicating shared processing resources.

More crucially, when we examined the relative change in performance from baseline to DT conditions (speed and stride time DTC), there was comparatively greater gait interference on the Subtraction and Clock task than the Motor response task in the 15m group. These findings indicate a gradient effect of DT interference across these secondary tasks, as hypothesised, and as supported by previous work (Al-Yahya et al., 2011; Beurskens & Bock, 2012; Hausdorff et al., 2005). Thus, visuospatial, working memory and information updating processes appear to each play a role in gait control that goes beyond divided attention and simple motor response discrimination.

In particular, the Subtraction task in our study appears to have caused the most motor interference in relation to baseline and the Motor task. This Subtraction task targeted higher-level attention, working memory and constant concentration/information updating (Mertens et al., 2006). Therefore, these processes may play a greater role in controlling gait than the visuospatial processes taxed in the Clock task. However, it is of note that the n-back task, which also targets EF working memory, did not affect gait comparatively more than the Motor task (as the Subtraction task did). This is contrary to what we would have expected, as working memory has previously been associated with greater DT costs, and correlated with fall-risk (Beurskens & Bock, 2012). Wrightson et al. (2016) recently showed that the Subtraction and n-back tasks were equivalent in

reducing stride time variability in young adults. However, the Subtraction task required constant responding throughout the walking trial, and this may have taxed working memory and updating more than the recognition response type of working memory targeted in the 2-back task (where participants only had to identify when a word was repeated, and not respond on every trial). Alternatively, considering the 2-back task also showed decreased accuracy in the DT condition, some resources may have been preserved for the gait performance, explaining why the gait DTC were not equivalent to the Subtraction task in comparison to the Motor task. Automatic verbal responses recording technology is now available which can be used to automatically record response times as well as accuracy, and could offer more detail of responses in a study such as this.

Analysis of ST baseline measures of gait and cognitive performance revealed several differences between the 5m and 15 groups. The 5m group had a slower mean gait speed, higher Subtraction task accuracy and faster Motor task RTs. These differences may be explained by the physically shorter (5m) walkway. Regarding the accuracy and RT differences, the shorter ST trial time used to match the shorter 5m DT walking trial may account for this; participants only had to subtract for 45s instead of 60s in the 15m group. The Subtraction task may increase in difficulty the longer concentration, working memory and information updating are taxed: i.e. the further from the start of the task you go, the more attention and working memory are taxed to continuously update the current number position, and the longer the participant must continuously subtract without distraction or lapses in attention. The slower ST gait speed in the 5m group may be due to the fact that there is considerably less time for steady state walking between turns, and also due to turn-related acceleration and deceleration. A 5m walkway may be too short to build up to a faster normal walking speed, in comparison to 15m. However, it should be noted that the ST speed reported in both distance groups here is slower than previously

reported normative data. Bohannan and Andrews (2011) published reference data showing mean speeds of 135.8cm/s (range: 127-144.7) for men and 134.1cm/s (range: 123.9-144.3) for women aged 20-29years. However, there is also much methodological variability in how these walking tests for normative data are conducted (e.g. variations in length of walkway used and gait analysis technology), and Bohannon and Andrews suggest these data may not be useful for normal gait tests that involve a turn. Thus, it was more pertinent here to examine the relative change in gait (DTC values) within the 5m and 15m groups.

Finally, we observed more DT changes in mean gait speed, speed DTC and stride time DTC values over the 15m walkway, with evidence of a hierarchical trend between the tasks. These findings indicate that the Subtraction and Clock tasks caused comparatively more interference than the Motor task alone. Therefore, it may be the case that a 5m walkway is too short (with too few steady state gait cycles and a less time for cognitive trials on the secondary task), to identify the changes in speed and DTC values observed over the 15m walkway. Some authors suggest that gait speed can only be measured reliably at distances of 6-10m (Montero-Odasso, 2006), yet these distances would be generally larger than what is feasible within a home. This has implications for generalising laboratory DT study findings over longer distances to multitasking during daily living in the home. While stride time changes were still observed at the shorter distance, it may be necessary in the laboratory to use a longer walkway to identify changes in performances, in order to further our understanding of the cognitive-motor link.

3.4.1 Conclusion

This controlled experimental design allowed us to assess the relative impacts of different secondary tasks, and helped to tackle many of the methodological variability problems

reported in the DT literature (Al-Yahya et al., 2011). As hypothesised, the executive DTs significantly affected walking gait, yet there was little evidence of walking interfering with cognitive accuracy (except on the 2-back task). There were also more changes from ST gait on the Clock, Subtraction and 2-back task in comparison to the Motor task, as expected. This highlights the relative role of higher-level attention and executive function in the control of gait, even within a young healthy adult sample. However, we cannot generalise these findings in young healthy adults to older adults or fall-risk clinical samples. Gait control has been evidenced to change with ageing, and so there is a need for further research to investigate the different executive processes underlying older adult gait control. This will require more controlled and comparative DT study designs, which could lead to more effective clinical DT screening assessment and rehabilitative training techniques, as reported in the next chapter.

IV

Chapter 4

Executive domain dual-task effects on gait in healthy young and community-dwelling older adults.

This chapter has been published in *Frontiers of Human Neuroscience*

Abstract

Executive processing has been associated with gait and falls in older adults. However, due to much methodological variability in the literature, it is still unclear which specific executive processes play a role in older adult gait control. The following chapter details an experiment using the dual-task paradigm in healthy young (n = 20) and community-based older adults (n = 17). This study analysed cognitive and gait performances in single-task and 4 different dual-task conditions. We directly compared two non-executive control tasks (motor response task and alphabet recitation task) to three different executive domain tasks (visuospatial Clock task, 2-back working memory task, and mental tracking/working memory Subtraction task). There were more changes in speed (slower) and stride time (longer) for the executive tasks, and particularly so in the older adult group. However, there were no differences between the young and older groups on baseline (single-task) or dual-task walking. This may be due to our sample of a relatively young (*M* = 61.88 years) and healthy older adult group, who may not have to compensate much to maintain gait control while dual-tasking. Further work should specifically compare older adults with and without a history of falls to examine the link between age-related cognitive declines.

4.1 Introduction

Falls while walking are a common problem for older adults globally, with fall-risk found to be associated with cognitive decline in older adults (Shaw, 2002; Sheridan & Hausdorff, 2007). Consideration of top-down processing mediating gait has grown with increasing evidence of a cognitive-motor link, through the use of the dual-task paradigm (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2008). This paradigm allows us to specifically examine the relationship between cognition, gait and falls, by asking participants to perform an attention-demanding task while walking (Montero-Odasso, Muir & Speechley, 2012). The change, or "cost", to performance is thus an indicator of limited shared cortical resources required for both tasks (Monterro-Odasso et al., 2012), and has been strongly linked to fall-risk in older adults (Lundin-Olsson et al., 1997; Verghese et al., 2002). Dual-task studies have shown that more attention and higher-level cognitive resources are required to maintain or control gait in older adults, presumably to compensate for or adapt to age-related decline in sensorimotor functions (Beurskens & Bock, 2012; Woollacott & Shumway-Cook, 2002). Liu, Chan and Yan (2014) propose that increased falls in older adults are a consequence of age-related impairments in neural motor outputs. This results in walking gait becoming more attention-demanding, necessitating increased cognitive control. This argument relates to compensation hypotheses of neural ageing, whereby high-functioning older adults counteract age-related sensorimotor decline by reorganized neurocognitive networks (Cabeza, Anderson, Locantore, & McIntosh, 2002; Park & Reuter-Lorenz, 2009).

Generally, older adults have a slower gait speed, reduced stride length and increased stride time variability in comparison to young adults during single-task walking (Beurskesn & Bock, 2012; Smith, Cusack & Blake, 2016). Slower usual gait speed has been shown to predict falls and fall-risk in community-dwelling adults (Abellan Van Kan

et al., 2009; Verghese, Holtzer, Lipton, & Wang, 2009). Kenny et al. (2013) provided normative values for usual gait speed in a nationally-representative sample of community-dwelling adults over the age of 50 (and without cognitive impairment) living in Ireland. The mean speed at 60 years of age for men was 141.0 cm/s (men shorter than 173cm) and 144.4 cm/s (taller than 173cm), and 134.7 cm/s (shorter than 160cm) and 138.7 cm/s (taller than 160cm) for women. In young adults, normative speeds have been reported as 135.8cm/s (range: 127-144.7) for men and 134.1cm/s (range: 123.9-144.3) for women aged 20-29years (Bohannan & Andrews, 2011). However, there are no accepted values for speed during dual-task walking, which is more akin to daily life where one or more concurrent tasks are carried out while walking (Smith et al., 2016). The growing body of dual-task research does show that older adults have greater dual-task changes in gait than younger adults which has been associated with future fall-risk (Beurskens & Bock, 2012; Beauchet et al., 2009; Dubost et al., 2006; Muir-Hunter & Wittwer, 2016). Most commonly, a greater reduction in gait speed is observed, with some studies reporting an increased stride time and stride time variability, and decreased stride length (Beauchet, Dubost, Aminian, Gonthier, & Kressig, 2005; Beurskens & Bock, 2012; Hollman, Kovash, Kubick & Linbo, 2007).

Two studies comparing the dual-task costs of a working memory subtraction task (counting backwards and serial subtracting) and a semantic working memory task (animal naming) found that cognitively healthy older adults slowed down for both DTs, and exhibited an increased stride variability (Montero-Odasso, Muir & Speechley, 2012; Theill, Martin, Schumacher, Bridenbaugh, & Kressig, 2011). These studies also assessed cognitively impaired older adults and found exacerbated effects during dual-tasking, in comparison to the healthy older adults. Dubost et al. (2006) also showed that a verbal fluency task was associated with a reduction in gait speed, and increase in mean stride

time and stride time variability in healthy older adults. However, other studies have found that gait variability is not affected by a subtraction task in healthy young or older "non-faller" adults, but it is for idiopathic older adult fallers (Springer et al., 2008).

In some cases, a reduction in speed (also seen in young adults and other samples) is considered to be an appropriate compensatory strategy for maintaining balance while attention and cognitive resources are taxed by the secondary task (Dubost et al., 2006). However, a recent review by Gomes et al. (2016) found that gait speed and stride variability are both considered good indicators of fall risk (and are most often assessed together in the literature). Dubost et al. (2006) established that stride time variability under dual-task conditions is not solely a by-product of reduced gait speed during dual-tasking in older adults, but is also significantly associated with the attention-demanding dual-task. Furthermore, increased stride time variability in usual and dual-task walking has been associated with both cognitive decline and fall-risk in older adults, and in some cases has been shown to be a more sensitive marker of falls than gait speed alone (Hausdorff, Edelberg, Mitchell, Goldberger & Wei, 1997). Therefore, increased stride time variability during dual-task walking in older adults indicates decreased stability due to the demands of the cognitive task (Hollman et al., 2007).

Recent reviews and meta-analyses of dual-task studies in older adults reveal that the type of secondary task matters in terms of its effects on gait performance, and that executive function tasks seem to incur greater dual-task costs in older adults (Al-Yahya et al., 2011; Chu, Tang, Peng & Chen 2013; Gomes et al., 2016). Chu et al.'s (2013) recent analysis suggests that mental tracking tasks are best evidenced to predict falls (in comparison to reaction time tasks and discrimination or decision-making tasks). Executive visuospatial processing has also been evidenced to have a greater effect on dual-task performance (Menant, Sturnieks, Brodie, Smith & Lord, 2014), and play a

greater role in determining fall-risk, in comparison to mental verbal task loads in older adults (Barra, Bray, Sahini, Golding & Gresty, 2006). Within an Irish older adult sample, neuropsychological tests of processing speed, short-term memory and sustained attention contributed to slower gait speed on both single and dual-tasks, with an additional specific role of executive function for the dual-task, but not single-task performance (Killane et al., 2014). Executive function and attention (but not visual-spatial, memory or global cognition) have also been shown to correlate with, and prospectively predict, falls in undiagnosed older adults (Mirelman et al., 2012a; see also Buracchio et al., 2011; Herman & Mirelman, 2010; Holtzer, Stern, & Rakitin, 2005). Some studies also report a dual-task cost on cognitive performance in addition to gait costs in older adults. Theill et al. (2011) showed a reduction in cognitive dual-task performance on the subtraction task (reduced number of subtractions), in addition to reduced speed, but no reduction in performance on a semantic dual-task (animal naming). These mixed findings may speak to the issue of apparent differential effects of varied dual-tasks.

Recent reviews also note the problem of large methodological variability in the literature in terms of the type of secondary task used, which makes comparisons across studies challenging (Al-Yahya et al., 2011; Chu, Tang, Peng & Chen 2013; Gomes et al., 2016). While executive domain tasks appear to have a greater impact on dual-task gait in older adults, executive control can be further subdivided into different processes, and different tasks can target different executive functions (e.g. visuo-spatial processing, semantic working memory, numerical tracking working memory). The overuse of general, non-specific cognitive or distractor tasks and the broad variability in the choice of target task have contributed to ongoing ambiguity regarding the relative contribution of specific higher-level processes to walking in older adults. Consequently, preliminary clinical screening and dual-task training studies have yielded mixed efficacy (Plummer-D'Amato

et al., 2008; Plummer-D'Amato et al., 2012; Taylor-Piliae, Latt, Hepworth, & Coull, 2012). For example, while some studies have shown improvements in gait speed following dual-task training (Silsupadol et al., 2009), Plummer-D'Amato et al. (2008) found that once weekly dual-task training had no greater effect on gait outcomes than balance training alone. However, the training dual-tasks used were not domain-specific, with no clear executive cognition components (spontaneous speech, alphabet recitation and a coin transfer task). Furthermore, a recent systematic review (Menant, Schoene, Sarofim & Lord, 2014) found that single and dual-task gait speed were equivalent in predicting falls. However, the authors do allude to the methodological variability of the literature perhaps influencing their findings (not all secondary tasks affect gait).

To address this ambiguity in the literature, this experiment employs a comparative dual-task paradigm to probe the effects of varied secondary higher-level executive tasks on young and older adult gait. We utilise domain-specific tasks to compare different executive function tasks, and non-executive motor and verbal responding tasks. A motor response (Motor) task and verbal alphabet recitation (ABC) task were used as simple attention-demanding control tasks without stimulus differentiation or decision-making components, while a visuospatial task (Clock task), noun working memory task (2-back task) and numerical tracking and working memory task (Subtraction task) were used to target executive functioning processes.

4.1.1 Aims and Hypotheses

The focus of this experiment is to examine the top-down cognitive control of gait during dual-tasking in older adults. The overall aim is to identify which higher-level cognitive function is most utilized or relied upon during dual-task gait performance (evident in linear measures of gait) in healthy older adults. Further, we aim to examine age-related

changes in gait control in order to make comparisons to fall-risk older adults, cognitively impaired older adults, and other clinical samples. We predict that older adults will have **slower ST (baseline) gait speeds**. We hypothesise that there will be a **reduction in speed**, an increase in stride time, and some **increase in stride time variability** (for the older group) during dual-tasking. We also predict that older adults will show a **greater dual-task change** in gait parameters than young adults. We hypothesise that **higher-level executive dual-tasks** will effect linear measures of gait (speed, stride time, stride time variability) comparatively more than basic attention-demanding motor and verbal response tasks, with greater effects in older adults.

4.2 Methods

4.2.1 Participants

A sample of 20 healthy young adults aged 18+ years (range: 19-28 years, *M* = 21.10, SEM = 0.40; 10 male) and 17 older adults aged 55+ years (*M* =61.88, SEM = 1.51; 6 male) was recruited as volunteers from Maynooth University campus and surrounding locality. Two older adult participants were identified as 52 years of age after recruitment, but their data were retained within the sample as their scores did not unduly influence the data, or fall outside 3xIQR of the group mean (only extreme outliers at 3xIQR were removed from the data set, to avoid loss of data). Demographically, it was noted that 6 of the older adults reported experiencing a fall in the 12 months previous (aged: 52, 61, 63, 68, 68, and 74). Exclusion criteria were screened by telephone checklist prior to the experiment and included: history of clinically diagnosed cardiovascular, psychological or neurological impairments (including any diagnosis of MCI or Dementia); any muscular or bone problems likely to cause balance/gait impairments, or severe uncorrected sensory impairments. The Maynooth University Research Ethics Committee approved all experiments, which were conducted in accordance with the Code of Ethics of the World Medical Association and the ethical standards of the APA. All participants gave written informed consent (see Appendix K) at the commencement of their participation.

4.2.2 Control Measures

For comparison between the age groups, the National Adult Reading Test (NART: Nelson, 1982) was used as a measure of pre-morbid intelligence (see Chapter 2 section 2.1.3). The older adults also completed the Falls Efficacy Scale-International (FES-I: Yardley et al., 2005), the Mini Mental State Examination (MMSE-2: Folstein, Folstein, & McHugh, 1975) and the Montreal Cognitive Assessment (MoCA: Nasreddine et al., 2005). See the

relevant sections in Chapter 2 for more detail and discussion of these measures (MMSE: section 2.1.1, MoCA: section 2.1.2, FES-I: section 2.1.4). Participant height (in centimetres) was also recorded to ensure there were no mean differences between the groups.

4.2.3 Gait Assessment

Participants completed 2 single-task (ST) walking gait trials, and 5 dual-task (DT) walking trials in total, walking along a straight 20m walkway on an empty open corridor. Each trial consisted of walking at a self-selected walking speed (SSWS) along the walkway four times, with an about-turn at each end; this allowed for enough steady-state gait cycles on each pass, to analyze normal walking gait outside of start/stop and turn slowing and acceleration. Gait data were recorded using two wireless inertial measurement sensors attached to the shank of the left and right leg (see Chapter 2, section 2.4) that were set to record for 75s and then stopped transmitting (this allowed enough time for the walking trials to be completed to the end). Gait data processing yielded 5 gait variables for analysis: gait speed (m/s); stride time (s); stride time variability (Coefficient of Variability: CV %); stride length (m); and stride length variability (CV %).

4.2.4 Dual-Tasks

Five tasks (described below), each 60s in length, were used in both seated cognitive trials and DT walking trials. A motor response (Motor) task and alphabet recitation (ABC) task were used as simple attention-demanding control tasks without stimulus differentiation or decision-making components. In contrast, a Subtraction task, an n-back (2-back) task and Clock task were utilized to target higher-level executive processes. The Motor, 2-back and Clock stimulus-response tasks were PC-generated (Dell Latitude 2.1GHz Intel

Pentium Processor laptop) in E-Prime. Auditory stimuli were presented via Dell USB plug-in speakers and which response accuracy and reaction time data were automatically logged. Participants completed the tasks while seated in the cognitive ST condition. In both ST and DT conditions, the participant held a wireless mouse in their dominant hand for tasks that required a button-press response. The ABC and Subtraction tasks required verbal responses without laptop-presented stimuli; these responses were manually recorded (with pen and paper) by the experimenter.

4.2.4.1 Motor task

The Motor task presented a single auditory tone (16-Bit WAV file; 1411kbps; 1000ms long) at randomly varied delay intervals, (500ms, 750ms or 1000ms). There was a 3000ms response window from stimulus onset. Participants were instructed to quickly respond with a wireless mouse button click (held in their dominant hand) and RTs were automatically logged in E-Prime. The single-stimulus and single-response made this task a simple attention-demanding control task without stimulus differentiation or decision-making components. Therefore, it was used as a control DT for comparison with the specific executive tasks.

4.2.4.2 ABC task

The ABC task required participants to verbally recite the alphabet, out loud, at a self-selected even pace for 60s. The number of correct letter recitations were logged by the experimenter, and a correct response rate (CRR) was calculated as number of correct responses divided by time (60s). This task, taxing basic verbal articulation, was also used as a comparative control task for comparison with the executive tasks that required verbal responses.

4.2.4.3 Clock task

The Clock task, was used to target visuospatial working memory decision task (adapted from Haggard, Cockburn, Cock, Fordham, & Wade, 2000). This task was carried out as described in Chapter 3: see section 3.2.3.2 for details.

4.2.4.4 n-back task

An auditory 2-back task was also employed to assess executive working memory (Owen, McMillan, Laird & Bullmore, 2005). This task was used as described in Chapter 3 section 3.2.3.3.

4.2.4.5 Subtraction task

The Subtraction task was used to specifically assess executive working memory (Mertens, Gagnon, Coulombe, & Messier, 2006). This task was used as described in Chapter 3, section 3.2.3.4. The experimenter recorded the number of correct responses and divided this by the time, to generate the CRR.

4.2.5 Procedure

After obtaining informed written consent, participants completed each of the control measures. Following this, the participants conducted two separate ST normal walking trials (averaged for regular pace characteristics), the seated ST cognitive condition, and combined walking plus cognitive DT trials. This design allows for the investigation of bi-directional DT effects on both gait and cognitive performance. All tasks were completed in one session lasting approximately 45mins in total (with shorts breaks offered to participants between tasks). One ST walking trial was completed before and after the cognitive ST and DT conditions, the order of which were counter-balanced across

participants (half completed cognitive ST condition first, half completed the DT condition first). Participants were instructed to walk the length of the walkway 4 times for each condition trial, at what they considered their normal pace (SSWS). No instruction was given regarding which task to prioritise in the DT condition. The dual-task change (DTC) was calculated as the relative percentage change from ST to DT performances for both the cognitive and gait measures (see Chapter 2, section 2.5). Participants were thanked for their time and debriefed at the end of the experiment session.

4.2.6 Statistical analysis

A MANOVA was used to compare the groups of the three NART-predicted IQ scores, and independent t-tests were used to compare the two age groups on height. Cognitive variables (accuracy, correct response rate, and/or RT), the 5 extracted gait variables, and the DTC values for both were analysed between and within the two age groups. A small number of values lying beyond 3 times the interquartile range were removed. Mixed between-within ANOVAs were used to analyse the effect of age group (between) and the tasks type (ST and DTs: within) on each of the individual gait measures (five 2x6 ANOVAs were conducted). Changes in performance between ST and DT were examined using paired samples t-tests, with differences between the groups on cognitive performances analysed using independent t-tests. DTC values (cognitive and gait) were also analysed using mixed factorial ANOVAs examining the effect of age group and task type (2x5 ANOVAs). Where there were significant main effects, follow-up analyses were conducted using one-way ANOVAs and independent t-tests. Levene's test of homogeneity of variances and Mauchly's test of sphericity were used, and the Greenhouse-Geisser correction was employed where the assumption of sphericity was

violated. Bonferroni-corrected alpha values were used where multiple comparisons were made, in order to avoid a Type 1 error.

4.3 Results

4.3.1 Group comparisons

There were no significant differences between the groups on NART scores [$F(3, 33) = 0.90$, $p = 0.453$, $\eta 2 = 0.075$], and no differences between the age groups in height [$t(35) = 1.46$, $p = 0.153$]. See Table 4.1 for all control measure mean and SEM values. All older adults had an MMSE score > 28 ($M = 29.41$, ± 0.19) and MOCA score > 23 ($M = 26.29$ ± 0.44). The older adult group reported a mean FES-I score of 25.76 (± 7.34) indicating only moderate concern of falling (Delbaere et al., 2010).

Table 4.1. *Mean and standard error of the mean (SEM) values for the NART based predicted IQ scores and height (cm) in both young and older groups, and the MMSE scores, MoCA scores and FES-I scores for older adults alone.*

	Young	**Older**
Measure	*M* (*SEM*)	*M* (*SEM*)
NART Full Scale IQ	115.45 (1.56)	110.18 (2.93)
NART Verbal IQ	113.30 (1.43)	108.47 (2.72)
NART Performance IQ	114.20 (1.40)	109.53 (2.61)
Height (cm)	174.00 (2.09)	168.47 (3.28)
MMSE	-	29.41 (0.19)
MoCA	-	26.29 (0.44)
FES-I	-	25.76 (1.78)

4.3.2 Gait Analysis

The mean (*M*) and standard error of the mean (*SEM*) values for all gait variables in each of the walking conditions (ST and DT) are shown in Table 4.2. There was a significant main effect of type of dual-task on gait speed and mean stride time only [speed: $F(5, 175) = 10.32$, $p < .001$, $\eta 2 = 0.228$; stride time: $F(3.12, 109.31) = 22.90$, $p < 0.001$, $\eta 2 = 0.396$]. However, there was no main effect for group [speed: $F(1, 35) = 0.94$, $p < .339$, $\eta 2 = 0.026$; stride time: $F(1, 35) = 0.77$, $p = 0.386$, $\eta 2 = 0.022$] or interaction effects [speed: $F(5, 175) = 2.06$, $p = .73$, $\eta 2 = 0.056$; stride time: $F(3.12, 109.31) = 0.85$, $p = 0.475$, $\eta 2 = 0.024$].

Follow up comparisons revealed that the younger group had a significantly slower speed ($p = .019$) on the ABC DT ($M = 1.14$, $SEM = 0.03$) compared to baseline ST walking ($M = 1.22$, $SEM = 0.02$): $F(5, 95) = 3.77$, $p = .004$. $\eta 2 = 0.166$. For the older group, gait speed was slower than baseline ($M = 1.23$, $SEM = 0.04$) on all DTs [$F(5, 80) = 7.92$, $p < .001$. $\eta 2 = 0.331$]; Motor ($M = 1.15$, $SEM = 0.03$, $p = .016$); ABC ($M = 1.14$, $SEM = 0.04$, $p = .048$); 2-back ($M = 1.10$, $SEM = 0.03$, $p < .001$); Subtraction ($M = 1.10$, $SEM = 0.04$, $p < .001$); Clock ($M = 1.10$, $SEM = 0.04$, $p = .001$). See Figure 4.1.

Table 4.2. *Mean (and standard error of the mean) values for speed, stride time, stride time variability (CV stride time), stride length and stride length variability (CV stride length) values for the single-task (ST) and dual-task (DT) conditions in the young and older adult groups: * indicates a significant change from ST to DT condition, ** indicates a significant difference from the Motor DT.*

Young Adults

Gait Measure	ST	Motor DT	ABC DT	2-back DT	Clock DT	Subtraction DT
Speed (m/s)	1.22 (0.02)	1.21 (0.03)	1.14* (0.04)	1.16 (0.03)	1.16 (0.03)	1.16 (0.03)
Stride Time (s)	0.91 (0.02)	0.93 (0.02)	0.98* (0.03)	0.97* (0.02)	0.98** (0.02)	0.98** (0.02)
CV Stride Time (%)	6.69 (0.18)	6.39 (0.13)	7.13 (0.25)	7.54 (0.50)	7.33 (0.29)	6.84 (0.28)
Stride Length (m)	1.10 (0.01)	1.11 (0.01)	1.10 (0.01)	1.11 (0.01)	1.13 (0.01)	1.13 (0.01)
CV Stride Length (%)	48.61 (0.90)	47.90 (0.78)	48.54 (1.00)	47.14 (0.84)	47.22 (1.04)	47.68 (1.02)

Older Adults

Gait Measure	ST	Motor DT	ABC DT	2-back DT	Clock DT	Subtraction DT
Speed (m/s)	1.23 (0.04)	1.15 (0.03)	1.14* (0.04)	1.10* (0.03)	1.10* (0.03)	1.10* (0.03)
Stride Time (s)	0.92 (0.02)	0.95* (0.02)	1.00* (0.04)	1.00** (0.03)	1.03** (0.02)	1.03** (0.04)
CV Stride Time (%)	7.02 (0.26)	7.04 (0.28)	6.85 (0.41)	6.99 (0.28)	7.25 (0.40)	6.83 (0.30)
Stride Length (m)	1.12 (0.01)	1.08 (0.01)	1.12 (0.01)	1.09 (0.01)	1.12 (0.01)	1.10 (0.01)
CV Stride Length (%)	47.67 (1.14)	49.95 (1.14)	47.21 (1.09)	49.91 (1.00)	46.65 (0.65)	49.98 (1.07)

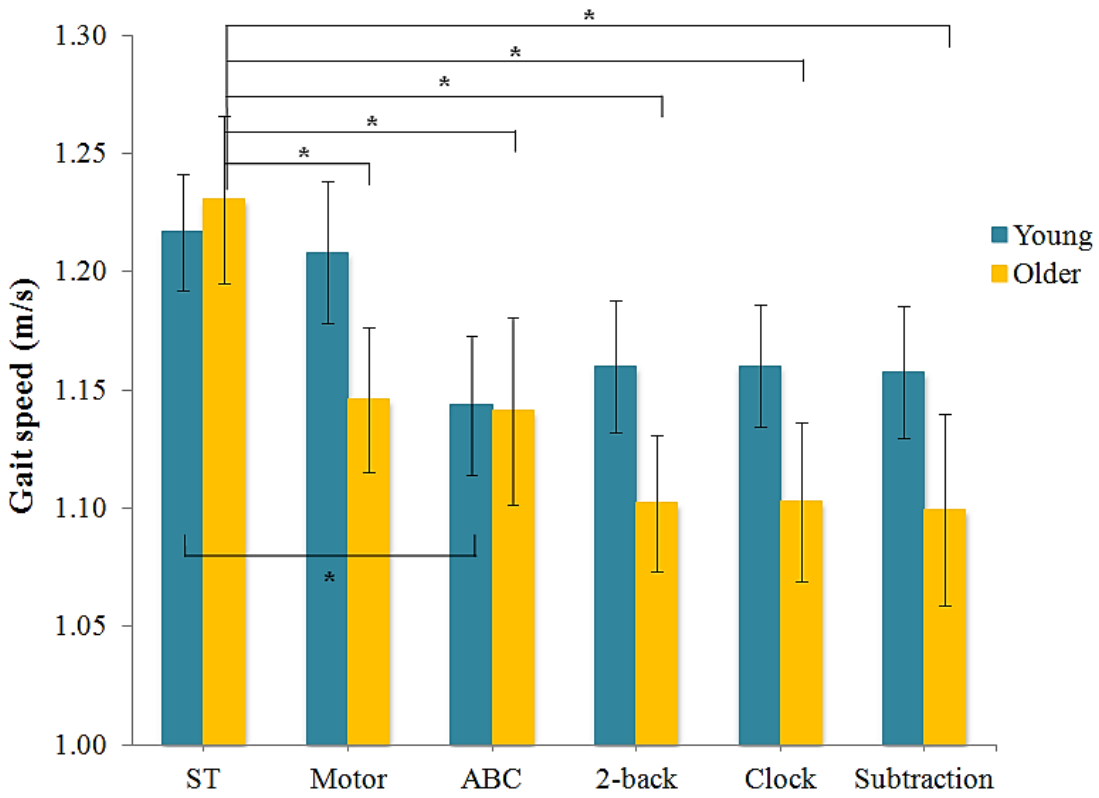

Figure 4.1. *Mean gait speed (m/s: +/- SEM) across single (ST) and dual-task (DT) conditions in both young and older adult groups (*indicates significance at the Bonferroni corrected alpha).*

Follow-up analyses of stride time also showed that in the younger group, stride times were longer than baseline (*M* = 0.91, *SEM* = 0.02) in the ABC (*M* = 0.98, *SEM* = 0.03, *p* = .011), 2-back (*M* = 0.97, *SEM* = 0.02, *p* = .021), Clock (*M* = 0.98, *SEM* = 0.02, *p* = .001) and Subtraction (*M* = 0.98, *SEM* = 0.02, *p* =.001) DT trials: *F*(2.46, 46.73) = 12.75, *p* = .000, η2 = .40. In addition, stride time was also greater on the Subtraction (*p* = .004) and Clock task (*p* = .003) than the Motor task (*M* = 0.93, *SEM* = 0.02), while there were no differences between ST and Motor DT stride time (*p* = .135).

For the older adult group, stride time was greater than baseline (*M* = 0.92, *SEM* = 0.02) on all DTs [*F*(2.92, 46.71) = 10.58, *p* < .001, η2 = .398]: Motor (*M* = 0.95, *SEM* = 0.02, *p* = .013); ABC (*M* = 1.00, *SEM* = 0.04, *p* = .030); 2-back (*M* = 1.00, *SEM* = 0.03, *p* = .006); Clock (*M* = 1.03, *SEM* = 0.03, *p* < .001); and Subtraction (*M* = 1.03, *SEM* =

0.04, p = .006). Stride times were also longer than the Motor task on the Subtraction (p = .03) and Clock task (p = .002)–as with the younger adults–as well as the 2-back task (p = .035: See Figure 4.2).

There were no main effects for task or group on stride time variability [task: $F(3.50, 101.39) = 1.36$, $p = 0.257$, $\eta 2 = 0.045$; group: $F(1, 29) = 0.41$, $p = .526$, $\eta 2 = 0.014$], mean stride length [task: $F(5, 170) = 1.46$, $p = 0.21$, $\eta 2 = 0.041$; group: $F(1, 34) = 0.81$, $p = .374$, $\eta 2 = 0.023$] or stride length variability [task: $F(5, 150) = 1.51$, $p = 1.90$, $\eta 2 = 0.58$; group: $F(1, 30) = 0.99$, $p = .327$, $\eta 2 = 0.032$]. There were also no interaction effects for any of the above (all $F < 2.25$, all $p > .05$).

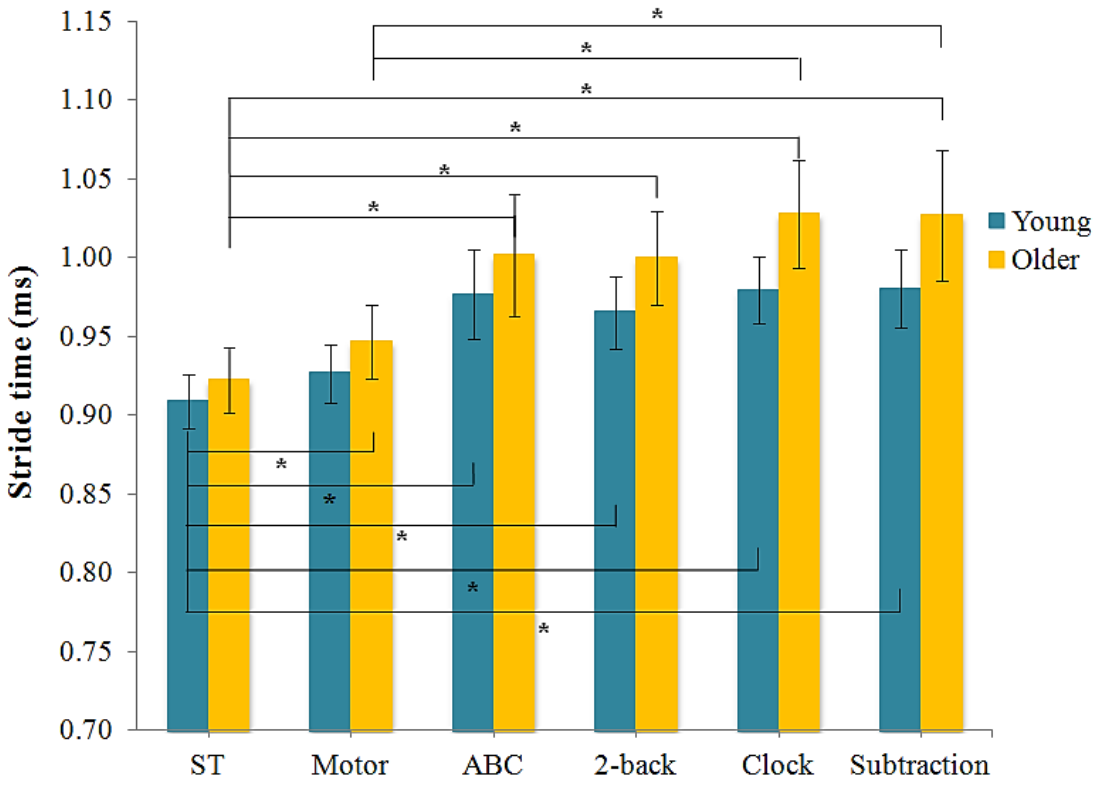

Figure 4.2 *Mean stride time (m/s: +/- SEM) across single (ST) and dual-task (DT) conditions in both young and older adult groups (*indicates significance at the Bonferroni corrected alpha).*

4.3.2.1 Gait DTC

DTC values (relative change from ST to DT) for each of the gait variables were compared across task type and between the age groups. The mean (and SEM) gait DTC values for each task type are presented in Table 4.3.

4.3.2.1.1 Speed DTC

There was a significant main effect of task type [$F(4, 140) = 2.77$, $p = .03$, $\eta p^2 = 0.073$] and group [$F(1, 35) = 7.26$, $p = .011$, $\eta p^2 = 0.172$] on speed DTC, but no significant interaction between task type and experiment group [$F(4, 140) = 1.12$, $p = .356$, $\eta p^2 = 0.031$]. (See Figure 4.3.) However, follow up comparisons showed no significant differences across task types within the groups [young: $F(4, 76) = 2.45$, $p = .053$, $\eta p^2 = 0.114$; older: $F(4, 64) = 1.53$, $p = .203$, $\eta p^2 = 0.088$], or between the groups: all $t < 2.53$, all $p > .016$, with Bonferroni corrected $\alpha = .01$.

Table 4.3. *Motor dual-task change* (*DTC %) values for speed, stride time, stride time variability (CV stride time), stride length and stride length variability (CV stride length) values for each dual-task* (*DT) conditions in the young and older adult groups.*

Young

Gait DTC	Motor DT	ABC DT	2-back DT	Clock DT	Subtraction DT
Speed DTC%	0.59 (1.65)	5.99 (1.65)	4.32 (2.19)	4.48 (1.54)	4.57 (2.07)
Stride Time DTC%	1.86 (0.68)	7.16 (1.71)	6.14 (1.61)	7.72 (1.51)	7.69 (1.42)
CV Stride Time DTC%	-1.02 (4.47)	2.41 (3.50)	9.24 (7.67)	5.53 (4.22)	-3.81 (2.44)
Stride Length DTC%	-1.23 (1.69)	-0.41 (1.43)	-1.11 (1.61)	-2.61 (1.21)	-3.69 (1.57)
CV Stride Length DTC%	-0.73 (2.62)	0.50 (2.75)	-2.50 (2.38)	-2.50 (2.28)	-4.68 (2.59)

Older

Gait DTC	Motor DT	ABC DT	2-back DT	Clock DT	Subtraction DT
Speed DTC%	6.56 (1.66)	7.22 (2.14)	10.20 (1.39)	10.17 (1.88)	10.82 (1.79)
Stride Time DTC%	2.56 (0.62)	8.12 (2.03)	8.28 (1.76)	11.08 (1.68)	10.76 (2.16)
CV Stride Time DTC%	2.20 (5.25)	-2.62 (3.84)	1.23 (4.17)	4.93 (6.79)	8.70 (9.07)
Stride Length DTC%	4.11 (1.80)	0.02 (1.96)	2.92 (1.43)	0.45 (1.77)	1.59 (1.49)
CV Stride Length DTC%	5.82 (3.66)	0.30 (3.89)	5.58 (3.15)	-0.57 (3.09)	5.78 (3.36)

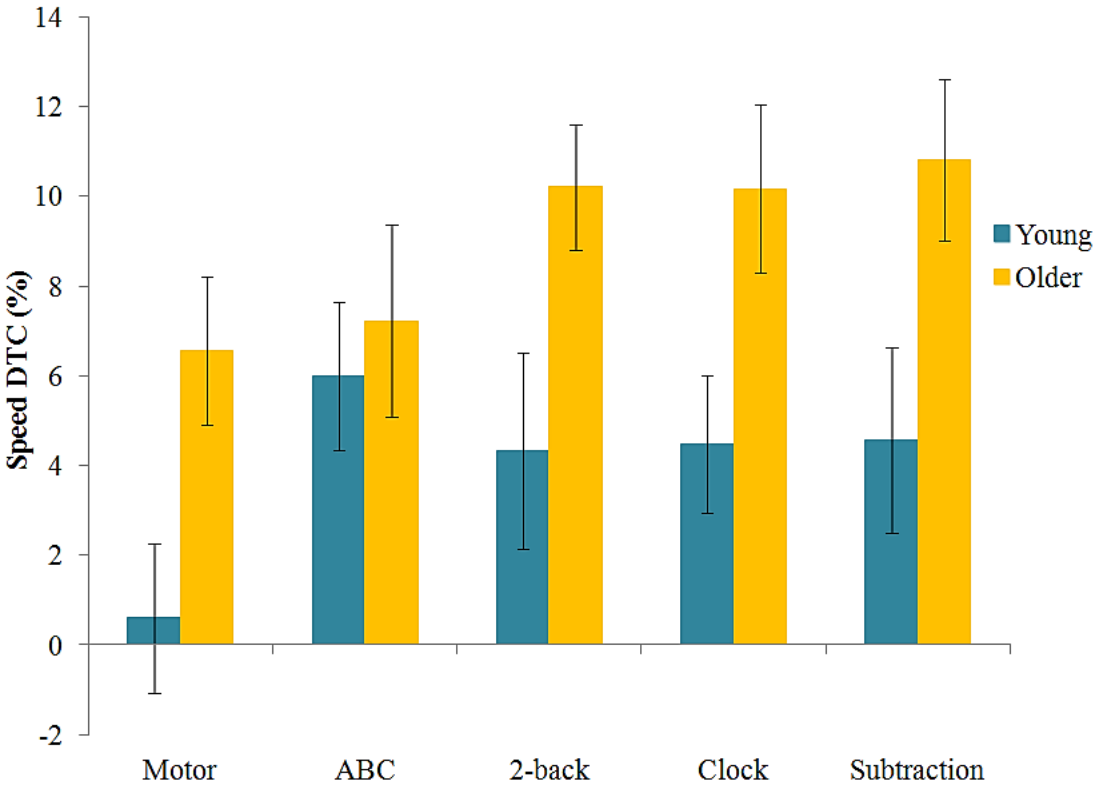

Figure 4.3 *Mean dual-task change (DTC) in speed (+/- SEM) for each dual-task in both young and older adult groups. Positive values indicate a cost in performance from ST to DT.*

4.3.2.1.2 Stride time DTC

There was a significant main effect of task type on stride time DTC [$F(4, 140) = 14.23$, $p < .001$, $\eta p^2 = 0.289$], but no main effect for group [$F(1, 35) = 1.36$, $p = .252$, $\eta p^2 = 0.037$], or interaction effect [$F(4, 140) = 0.60$, $p = .662$, $\eta p^2 = 0.017$]. Follow-up tests in the young group revealed that stride time DTC was greater for the ABC ($M = 7.16$, $SEM = 1.71$, $p = .035$), 2-back: ($M = 6.14$, $SEM = 1.61$, $p = .045$), Subtraction: ($M = 7.69$, $SEM = 1.42$, $p = .001$), and Clock task ($M = 7.72$, $SEM = 1.51$, $p = .002$), in comparison to the Motor DTC ($M = 1.86$, $SEM = 0.68$): $F(4, 76) = 8.52$, $p < .001$, $\eta p^2 = 0.310$. In the older group, the 2-back ($M = 8.28$, $SEM = 1.76$, $p = .018$), Subtraction ($M = 10.76$, $SEM = 2.16$, $p = .01$) and Clock task ($M = 11.08$, $SEM = 1.68$, $p = .001$) DTC were larger than

the Motor task (M = 2.56, SEM = 0.62): $F(4, 64) = 6.37$, $p < .001$, $\eta p^2 = 0.285$. However, there was no difference between stride time DTC on the Motor task and the ABC task (M = 8.12, SEM = 2.03, $p = .141$) in the older group (see Figure 4.4).

4.3.2.1.3 Stride Time Variability, Stride Length and Stride Length variability DTC

There were no main effects of task type or group on stride time variability DTC [task type: $F(4, 132) = 0.31$, $p = .869$, $\eta p^2 = 0.009$; group: $F(1, 33) = 0.19$, $p = .670$, $\eta p^2 = 0.006$], stride length DTC [task: $F(4, 136) = 1.76$, $p = .141$, $\eta p^2 = 0.049$; group: $F(1, 34) = 5.72$, $p = .022$, $\eta p^2 = 0.144$], or stride length variability DTC [task: $F(4, 136) = 1.19$, $p = .316$, $\eta p^2 = 0.034$; group: $F(1, 34) = 3.10$, $p = .087$, $\eta p^2 = 0.084$].

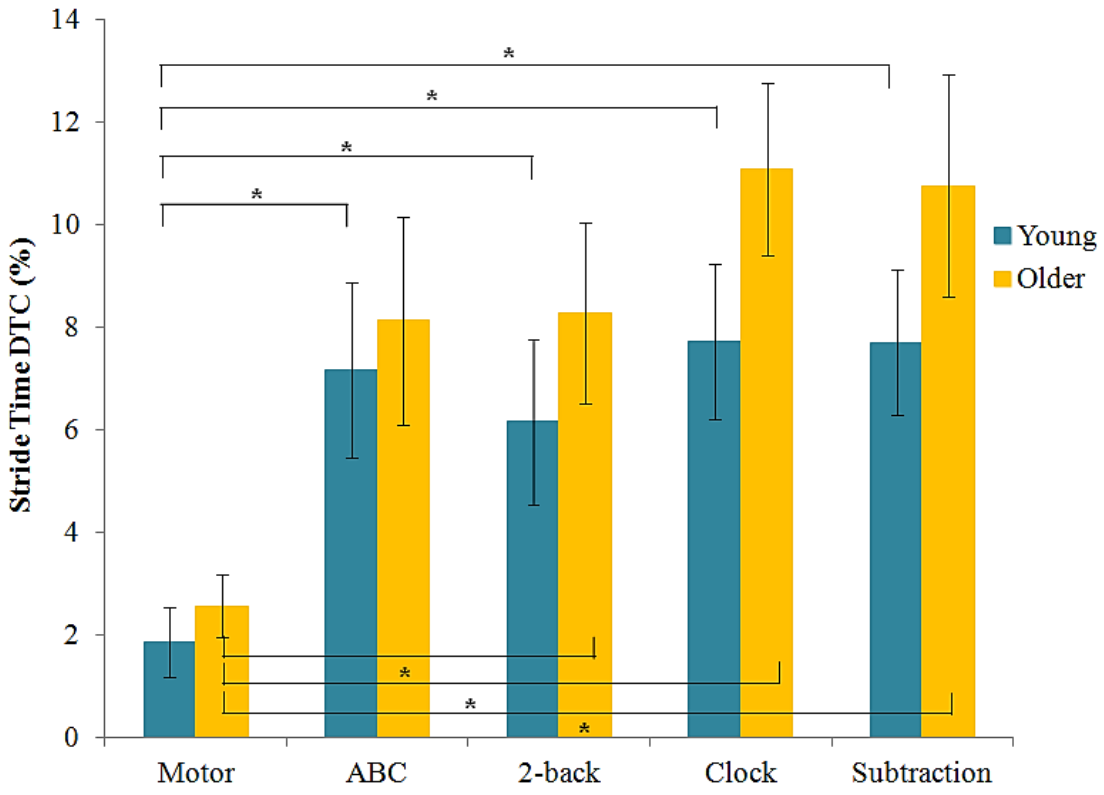

Figure 4.4. *Mean dual-task change (DTC) in stride time (+/- SEM) for each dual-task in both young and older adult groups (* indicates significance at the Bonferroni corrected alpha).*

4.3.3 Cognitive Analysis

The mean (and SEM) accuracy and RT responses for the cognitive tasks are presented in Table 4.4. Comparing the groups on cognitive performances revealed an age-related difference on the Clock task only [ST: $t(35) = 3.37$, $p = 0.002$; DT: $t(34) = 2.71$, $p = 0.01$], whereby the younger group were more accurate in both the ST and DT condition (ST: $M = 56.00$, $SEM = 5.80$; DT: $M = 50.74$, $SEM = 5.35$) than the older adult group (ST: $M = 30.35$, $SEM = 4.65$; DT: $M = 32.47$, $SEM = 3.87$). There were no differences between the age groups on any other ST or DT cognitive performances: Motor [ST: $t(35) = -1.63$, $p = .112$; DT: $t(34) = -1.18$, $p = .246$]; ABC [ST: $t(35) = -0.96$, $p = .344$; DT: $t(26.07) = -0.84$, $p = .410$]; 2-back [ST: $t(35) = 0.66$, $p = .513$; DT: $t(34) = 0.90$, $p = .376$]; Subtraction [ST: $t(35) = -2.23$, $p = .032$; DT: $t(34) = -2.92$, $p = .006$].

Within each group, changes in accuracy and RT from ST to DT conditions were examined. On the Motor task alone, the younger group revealed a significant decrease in RT from ST ($M = 587.75$, $SEM = 24.19$) to DT ($M = 653.66$, $SEM = 22.42$) conditions; $t(19) = -4.72$, $p < .001$. However, this effect was not observed in the older group: $t(15) = -0.59$, $p = .566$. No other task exhibited differences between ST and DT response performance for either the young [ABC: $t(18) = 1.98$, $p = .063$; 2-back: $t(18) = -1.02$, $p = .32$; Subtraction: $t(18) = 0.88$, $p = .388$; Clock: $t(18) = 0.94$, $p = .362$] or older group [ABC: $t(16) = 2.89$, $p = .011$; 2-back: $t(16) = -0.75$, $p = .466$; Subtraction: $t(16) = 1.07$, $p = .300$; Clock: $t(16) = -0.48$, $p = .636$].

4.3.3.1 Cognitive DTC

Concurrently, there were no differences in the calculated DTC (%) across the cognitive tasks: no significant main effect for task type [$F(1.58, 53.55) = 3.18$, $p = .061$, $\eta p^2 = 0.085$], or group [$F(1, 34) = 0.001$, $p = .980$, $\eta p^2 = 0.000$], and no interaction effect

[$F(1.58, 53.55) = 0.25$, $p = .729$, $\eta p^2 = 0.007$]. See Table 4.4 for *M* and *SEM* DTC % values.

Table 4.4. *Mean* (*and SEM) dual-task performance values* (*RT, CRR and ACC) for each task in single-task* (*ST) condition and dual-task* (*DT) condition and dual-task change relative change values* (*DTC%) for each, in the young and older adult groups*
.

	Young			**Older**		
Task	ST	DT	DTC%	ST	DT	DTC%
Motor RT (ms)	556.08 (11.49)	653.66 (22.42)	0.12 (0.02)	633.88 (41.99)	697.40 (30.59)	0.12 (0.08)
ABC CRR	2.24 (0.18)	1.98 (0.16)	7.64 (4.14)	2.59 (0.32)	2.24 (0.27)	11.19 (13.57)
2-back ACC (%)	93.05 (2.06)	95.21 (1.39)	0.01 (0.06)	91.35 (1.36)	93.18 (1.82)	-0.02 (0.02)
Clock ACC (%)	56.00 (5.80)	50.74 (5.35)	0.02 (0.15)	30.35 (4.65)	29.38 (2.48)	-0.20 (0.22)
Subtraction CRR	0.48 (0.06)	0.42 (0.05)	2.64 (6.96)	0.67 (0.06)	0.63 (0.05)	1.72 (5.78)

4.4 Discussion

In summary, apart from a difference between groups on speed DTC, we did not see any differences in gait characteristics between young and older adults in baseline ST or DT walking. There were changes in gait speed and stride time under dual-task conditions across both age groups (as predicted). Overall, EF tasks had slowest speed and longest stride times, and greater changes in these gait characteristics, particularly in the older group. However, we did not see any changes in stride time variability, stride length or stride length variability. There were also no relevant changes in cognitive performance beyond slower motor responses on the DT condition in young adults, and an age-related decline in visuospatial processing (in both ST and DT conditions).

We hypothesized that older adults would have slower gait speed during normal baseline (single-task) walking, yet we found no differences between the groups on any baseline gait measure. Previously, gait velocity at usual pace has been shown to decline with age (Beurskesn & Bock, 2012; Smith, Cusack & Blake, 2016), with speed evidenced as a predictor of falls, and shown to identify fall-risk in community-dwelling fallers (Abellan Van Kan et al., 2009; Verghese et al., 2009). It is of note that the ST gait speeds reported here are slower than reference values reported elsewhere (Bohannan & Andrews, 2011; Kenny et al., 2013). The reason for this is unclear, but it did not seem to have a "floor" effect as we were still able to see changes in gait (slower speed) from baseline to DT conditions, and as both groups were slower at baseline, we could still compare across groups.

One explanation for why we did not observe age-related changes in gait at baseline may be that our older adult sample was comprised of relatively healthy and active individuals (volunteering from the community and community groups), with a comparatively young mean age ($M = 61.88$) compared to samples reported in other studies.

Furthermore, recent literature has also failed to identify age-related differences in spatiotemporal gait variables during normal single-task walking (Terrier & Reynard, 2015). Normal walking trials are relatively simple to perform, particularly in the controlled environment of the laboratory (a straight, flat, indoor pathway with no distractions or obstructions). Perhaps it is not always possible to identify age-related differences in gait characteristics when full attention can be dedicated to walking on an easy pathway. This has been shown in a longitudinal prospective study of falls in community-dwelling older adults, where usual walking speed did not predict falls (where age and sex are taken into account; Mirelman et al., 2012). A more challenging pathway (with bends, obstacles and active navigation) for normal walking may be necessary to identify usual gait control differences for active, healthy, older adult samples. It may be that healthy active older adults have adequate bottom-up motor functioning for walking straight comparatively to younger adults. A more challenging pathway may highlight the top-down deficits in the cognitive control of gait and exhibit differences between younger and older adults. We also did not observe any differences between the groups on DT gait performances for any task. Yet, we did see more occurrences of changes in speed and stride time for the older group than young group. Therefore, DT trials may be more sensitive to identifying subtle gait changes.

Both groups showed a trend of walking slower on all DTs: whereas the young adults were only significantly slower on the ABC task–the reason for this is not clear–the older adults were significantly slower on all DTs, with a trend of slowest speeds on the three executive tasks (2-back, Subtraction, Clock). However, in contrast to our predictions, there were no differences in the relative change (DTC) in speed across tasks for either group. Previous studies have shown greater dual-task slowing in older adults who are concurrently performing subtraction and verbal fluency tasks (Dubost et al., 2006;

Theill et al., 2011). Both groups also had increased stride times on the ABC, Clock, 2-back and Subtraction tasks. More importantly, we also saw comparatively greater changes in stride times on the Subtraction and Clock task than the simple attention demanding Motor task. This comparison shows that EF tasks affect stride time more than simple attention demanding tasks.

While the trend in the data shows that the 2-back task (as well as the ABC task) also elicited a substantial DTC in stride time than the motor task, this was not to reach the significant change found with the Subtraction and Clock task. Interestingly, both the Subtraction and 2-back task can be said to tax working memory (Mertens et al., 2006; Owen et al., 2005), however, it may be the case that the 2-back task was not as challenging as the Subtraction task, as it only required a response to target trials (say "MATCH" when a word is repeated), whereas serial subtracting requires constant responding and perhaps a greater mental tracking load. Some have suggested that changes in gait on tasks that require constant articulatory responding may be attributable to competing motor and respiratory processes necessary for gait (Dault, Yardley & Frank, 2003; Yardley, Gardner, Leadbetter & Lavie, 1999). The advantage of this study design is that we used both a motor response and articulation control task (Motor and ABC tasks), and so could make a direct comparison. While the Subtraction and Clock tasks were not significantly different from the ABC, the trend in each instance showed greater changes in gait characteristics on these EF tasks than the Motor and ABC DTs.

While the changes in speed and stride time are in-line with our predictions, we did not see changes in variability as expected. We predicted that variability would increase in older adults during dual-task walking, as an indicator of instability while cognitive resources were taxed with the EF tasks (Hollman et al., 2007). Other studies have shown increases in stride time variability in older adults under DT conditions (Dubost et al.,

2006; Montero-Odasso et al., 2012; Theill, et al., 2011). However, there are inconsistencies in the literature, with other authors reporting no variability changes in older adults, or only specifically for older idiopathic fallers (Springer et al., 2006).

Overall, there is gradient trend that the executive tasks interfered with gait speed and stride time the most, and particularly in the older adults (although this trend only reached significance in the instances outlined above). The tasks which taxed visuospatial decision making and mental tracking/working memory affected gait more than other tasks in this study. This implies an overlap of concurrent processing for these tasks and walking performance. Given that participants were not told to prioritize either task, the change in gait speed and stride time, but not in cognitive performance, suggests that priority was given to the maintenance of the cognitive task performance. However, the observed changes in gait do not imply instability, but rather more likely reflect appropriate compensatory changes to maintain stability while attention and cognitive resources are taxed.

4.4.1 Conclusion

The experiment reported here sought to identify the key higher-level cognitive processes underlying walking gait and falls in older adults. This controlled experimental design allowed us to assess the relative impacts of different secondary tasks, in an attempt to tackle some of the methodological variability problems reported in the DT literature (Al-Yahya et al., 2011; Gomes et al., 2016). The novel inclusion of two control (non-executive) DTs (targeting the verbal/motor functions necessary for responding on the other EF tasks), allows us to identify the additional impact of EF processing DTs. These results suggest that the EF Subtraction and Clock tasks had the largest DT effects on speed, stride time, and the relative change in stride time while dual-tasking. This was particularly evident

for the older adults where the Subtraction and Clock tasks displayed comparatively longer stride times than ST and the in-built control Motor task. However, we did not see the expected greater change in speed and increases in variability expected in the older adult group (as shown in previous literature). This may be due to our healthy and relatively young older adult sample, which may not have to compensate much to maintain gait control while dual-tasking. Further research should focus specifically on older adults with and without a history of falls, to investigate potential differences in neurocognitive ageing and falls (as is examined in the next chapter).

Chapter 5

Investigating electrophysiological markers of executive impairment in older adult fallers.

This chapter has been published in *Frontiers of Human Neuroscience*

Abstract

Higher-level executive functions are suggested to play a key role in gait control and fall-risk in older adults, but the specific underlying neurocognitive processes remain unclear. Here, we report an experiment which investigated the cognitive and neural processes related to older adult gait and falls. We compared normal walking gait, seated cognitive performances and concurrent event-related brain potentials (ERPs) in healthy young (n = 20) and older adults (n = 13), to older adult fallers (n = 8). This study employed a working memory n-back task, sustained attention and response inhibition colour-word Stroop task, and a comparative attention-demanding stimulus-response Motor task. There were no significant differences between any of the groups on gait characteristics, with only age-related differences evident on behavioural cognitive measures. No differences were found between older fallers and non-fallers in executive function performance. However, an initial late-positivity, considered a potential early P3a-like component, was evident on the Stroop task for older non-fallers, which was notably absent in older fallers and young adults. This difference in the P3a-like component could underlie, or at least contribute to, the older adult group's respective fall-status.

5.1 Introduction

Both gait and cognitive impairments have been commonly reported to occur with ageing, with previous literature and the preceding experiment highlighting that higher-level executive functions appear to play a role gait control. Executive performances have also been specifically associated with falls in older adults (Buracchio et al., 2011; Springer et al., 2006). It may be the case that age-related decline in neural motor outputs necessitates more top-down attentive motor control during walking (Liu, Chan & Yan, 2014). However, the specific executive domains and underlying neurocognitive processes remain unclear.

One way to further elucidate the contributions of higher-level cognitive processes to gait control is with the use of neuroimaging and physiological recording approaches. Recent studies have begun to use functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS) and electroencephalography (EEG) techniques to investigate the neural underpinnings of gait (Holtzer et al., 2011; Marcar, Bridenbaugh, Kool, Niedermann, & Kressig, 2014; Rosano et al., 2012; Yuan, Blumen, Verghese & Holtzer, 2015). Fall-related executive function (EF) decline, slower gait speed and diminished dual-task gait capacity have been associated with differential functioning and structural changes in frontal areas of the brain (Gunning-Dixon & Raz, 2003; Harada, Miyai, Suzuki, & Kubota, 2009; Holtzer et al., 2011). For example, a number of neuroimaging studies have found increased frontal region activation in young adults during dual-task walking with specific executive serial subtractions and verbal fluency tasks (Mirelamn et al., 2014; Holtzer et al., 2011). Rosano et al. (2012) found that smaller prefrontal area volume in older adults was associated with slower gait speed that may be attributed to slower cognitive processing. In addition, Harada et al. (2009) suggest

that the involvement of the left PFC may be specifically related to age-related decline in gait control capacity in older adults. Furthermore, stimulation to the left prefrontal cortex (PFC) using transcranial direct current stimulation (tDCS) has been shown to improve postural control and reduce changes in gait during dual-task walking in healthy young and older adults (Manor et al., 2016; Zhou et al., 2014).

In comparison to fNIRS, electroencephalogram (EEG) event-related potential (ERP) measurement offers higher temporal resolution recordings from the whole scalp (Beurskins, Steinberg, Antoniewicz, Wolff & Granacher, 2016). Increasingly, changes in frontal neuroelectrical activation, and specifically the P2 (approximately 150-250ms post-stimulus) and P3 (occurring after 300ms) waveform, have also been associated with ageing and executive function (Korsch, Frühholz & Herrmann, 2016; O'Connell et al., 2012; Polich, 2007). P2 amplitude has been shown to increase with ageing, where the P3 component appears later and with diminished amplitude in older adults (on working memory and Stroop tasks: McEvoy et al., 2001; West and Alain, 2000; Zurrón et al., 2014). The P3 component is often sub-divided into an early P3a and later P3b (Eppinger et al., 2007; Polich, 2007). The P3a is associated with frontal stimulus-driven attention processes, with the more posterior (temporal-parietal) P3b component associated with attention and memory processing, and more specifically EF stimulus evaluation and Stroop task processing (Killikelly & Szűcs, 2013; Polich, 2007; Zurrón et al., 2014). Recently, Korsch et al. have shown that an executive stimulus-response-conflict task induced greater P2 amplitudes, and increased P3 modulation for incongruent trials, in older adults. Others have also shown that P2 and P3 amplitudes are increased on incongruent trials (Gajewski et al., 2008; West et al., 2004), suggesting these components are related to an increased evaluation of the stimulus and conflict processing (Korsch et al., 2016).

While there is little research comparing EEG-recorded ERPs between faller and non-faller older adults, some studies suggests a link between P3 amplitude relating to executive function (inhibition and working memory) and physical activity in older adults (Chang, Huang, Chen, & Hung, 2013; Fong, Chi, Li, & Chang, 2014). Furthermore, a study of visual-spatial attention revealed an association between fall-risk and a greater N1 amplitude for poorer discrimination of task-irrelevant stimuli (in the left-field), and a larger P3 amplitude for target processing in low discrimination conditions (Nagamatsu, Munkacsy, Liu-Ambrose, & Handy, 2013). A few studies have been published which use wireless EEG recordings during single-and dual-task walking on a treadmill. Gait speed has been shown to decrease while alpha and beta band frequencies increase in frontal and central brain regions with additional cognitive and motor loads during dual-tasking in young adults (Beurskens et al., 2016). This study indicates that motor performance changes during dual-task walking are reflected in modulated neural activity, and due to an increased cognitive load during dual-task walking. This supports theories of top-down cognitive control of dual-task walking. Young adults also exhibit altered EF-related N2-P3 components during dual-task walking with an inhibitory control Go/No-Go task (De Sanctis, Butler, Malcolm, & Foxe, 2014). A more recent study comparing young and older adults found that while younger adults modulated early N2 and later P3 components during dual-task walking, older adults only exhibited modulation of later inhibitory-related amplitudes (Malcolm, Foxe, Butler & De Sanctis, 2015). This study found that older adults had increased P3 amplitudes while walking and performing a Go/No-Go response inhibition task, which the authors suggest reflects an age-related impairment in cognitive resource allocation.

Taken together, these findings indicate a greater need for cognitive control neural compensation for maintaining a successful normal gait in older age, and for dual-task

walking in both young and older adults. Liu, Chan and Yan (2014) propose that increased falls in older adults are a consequence of age-related impairments in neural motor outputs, resulting in walking gait becoming more attentionally-demanding, necessitating increased cognitive control. This argument relates to compensation hypotheses of neural ageing (Cabeza, Anderson, Locantore, & McIntosh, 2002; Park & Reuter-Lorenz, 2009). Park and Reuter-Lorenz (2009) posit that age-related over-activation of frontal areas suggests compensatory neural recruitment. Within these theoretical frameworks, older-adult fallers (without peripheral physiological impairment such as muscular or skeletal problems) could be considered to lack the plastic reorganization or compensatory over-activation necessary to circumvent age-related cognitive decline.

While the continued advancement of mobile-EEG recording will surely enhance understanding of the supraspinal activity underlying gait, the current study aimed to utilise accessible and applicable methods which could potentially translate to a clinical setting. This experiment aims to establish if event-related potential (ERP) markers of executive impairment can be found in older fallers compared to older non-fallers, by comparing executive working memory and sustained attention/conflict processing performances, with gait performance and history of falls status. An n-back and Stroop task are employed to target these two different types of executive functions (EF) which have been shown to correlate with gait, falls, and greater dual-task costs (Beurskens & Bock, 2012), and which also have previously defined age-related ERP components for comparison (Gajewski & Falkenstein, 2014; Zurrón et al., 2014). If we can identify a specific neuropsychological task or ERP marker of fall-risk in otherwise healthy older adults while seated, this would allow for an accessible and easily-administered alternative clinical screening procedure.

5.1.1 Aims and Hypotheses

In this experiment, we investigate normal walking gait, n-back and Stroop executive function (EF) performances and the associated ERPs, in healthy young and older adults, and older adult fallers. The aim is to investigate if there are EF-related event-related potentials (ERPs) that could act as a marker or indicator of fall-risk in healthy older adults. The main hypotheses are: 1) there will be subtle gait impairments (slower speed, increased stride time and stride time variability) in older adult fallers in comparison to non-fallers and young adults (in line with previous research: Hausdorff, Rios, & Edelberg, 2001; Verghese et al., 2009); 2) age-related and fall-related poorer EF performances will correlate with slower gait speed and; 3) EF-related later ERP components (e.g. N2, P2, P3 in line with the literature outlined above) will reflect diminished behavioural and gait performances in fallers compared to non-fallers, and compared to younger adults. More specifically, we want to investigate if P3 amplitude is reduced in older adults (as previously reported by Mager et al., 2007; Zurrón, Lindín, Galdo-Alvarez, & Díaz, 2014), and more so in older fallers, who may have limited available neural resources for allocation to task demands.

5.2 Methods

5.2.1 Participants

This study recruited a sample of 20 healthy young adults (10 male; mean age = 21.85) and 21 older adults divided into a group of 13 healthy older "non-faller" (ONF) adults (6 male; mean age = 70.83) and 8 older "fallers" (OF) adults (3 male; mean age = 63.75). All participants were volunteers from Maynooth University campus and the surrounding locality. Adults were classified as older fallers is they reported at least one fall in the 12 months prior to testing (via a self-report fall history questionnaire: Chapter 2, section 2.1.5), or in the 6 months following testing. Fall incidence post-testing was monitored via monthly fall-calendars on which participants noted daily if they had experienced a fall or not, and returned the calendar via post at the end of the month. Falls were defined as "a sudden, unintentional change in position resulting in landing at a lower level (floor, ground or on an object), other than as a consequence of health/medical issues (sudden paralysis, epileptic seizure, medications, or other sickness) or overwhelming external force" (adapted from Feder et al., 2000; and Tinetti, Baker, Dutcher, Vincent & Rozett, 1997). Falls were considered idiopathic, based on the questionnaire responses and the exclusion criteria for relevant diagnoses.

Exclusion criteria were screened by telephone checklist prior to the experiment and included: history of clinically diagnosed cardiovascular, psychological or neurological impairments (including any diagnosis of MCI or Dementia); any muscular or bone problems likely to cause balance/gait impairments, or severe uncorrected sensory impairments. The Maynooth University Research Ethics Committee approved this experiment protocol. All participants gave written informed consent (see Appendix L) at the commencement of their participation, and the experiment was conducted in

accordance with the Code of Ethics of the World Medical Association and the ethical standards of the APA.

5.2.2 Control Measures

A number of control measures were taken for comparison across the groups, in an attempt to discount some confounding factors. Participant height (in centimetres) was recorded to ensure there were no mean differences between the groups. The National Adult Reading Test (NART: Nelson, 1982) was also completed by all participants as a measure of pre-morbid intelligence (see Chapter 2 section 2.1.3). Additionally, the older adults (both ONF and OF) also completed the Falls Efficacy Scale-International (FES-I: Yardley et al., 2005), the Standardized Mini Mental State Examination (SMMSE: Molloy, Alemayehu, & Roberts, 1991) and the Montreal Cognitive Assessment (MoCA: Nasreddine et al., 2005). See Chapter 2 for more detail and discussion of these measures (MMSE: section 2.1.1, MoCA: section 2.1.2, FES-I: section 2.1.4).

5.2.3 Gait Assessment

A straight 15m walkway on an open, empty corridor was used for walking trials in this experiment. This distance allowed for extraction of steady pace kinematic gait data using the previously outlined algorithm (see Chapter 2, section 2.4.2), and was within the physical space confinements of the laboratory at the Department of Psychology, Maynooth University. Participants were asked to walk along the walkway 4 times at their usual pace (self-selected walking speed: SSWS), for each trial. Two trials of SSWS were conducted and averaged to get a better measure of usual ("normal") walking characteristics. Gait data were recorded in the same way as previous chapters, with temporal gait data extracted from the kinematic sensor data (see Chapter 2, section 2.4).

Speed, stride time, stride time variability (CV stride time), stride length and stride length variability (CV stride length) were the dependent variables.

5.2.4 Cognitive tasks

Participants were seated in a quiet, dim-lit room in front of an E-Prime presentation laptop (Dell Latitude D600 Pentium Laptop, with a 2.1GHz Intel Pentium Processor and 14 inch colour monitor). Three tasks were utilized (detailed below) which targeted attentive motor responding (Motor task), response inhibition (Stroop task) and working memory (n-back task). Task-specific instructions were given on-screen and verbally at the start of each task. Where relevant, response accuracy and reaction times (RT) were recorded automatically in E-Prime.

5.2.4.1 Motor task

The Motor task, as described in the previous chapter, was once again utilized as a non-executive control task, assessing motor response times to a single tone stimulus (see Chapter 4, section 4.2.4.1). The stimulus properties and response window were the same as previous: 16-Bit WAV file; 1000ms long; 1411kbps bit rate with a 3000ms response window and variable inter-stimulus delay (500ms, 750ms or 1000ms). However, for this study, the task consisted of 1 test block with 70 trials. Participants were instructed to respond as quickly as possible by pressing the left button on a wireless mouse, and response times (RTs: ms) were automatically logged in E-Prime.

5.2.4.2 1-back task

An n-back working memory paradigm was again utilized to assess updating/working memory performance (Dobbs & Rule, 1989; Owen, McMillan, Laird & Bullmore, 2005;

Wilhelm, Hildebrandt, & Oberauer, 2013). Where previous chapters utilised an auditory noun n-back task, this chapter employed a visual 1-back task. We decided to use an easier 1-back version of the task for the remainder of the participants in this study. Visual stimuli consisted of grey rectangular placeholders containing the number 1, 2, 3, 4 or nothing (a blank shape) presented over a white background on screen. The stimuli remained on screen for 1800ms, with a 500ms fixation between trials. Participants responded to each trial by pressing the numbered key (1, 2, 3 or 4) on the keyboard corresponding to the number presented in the previous trial (1-back). If the previous trial was blank, no response was required. This 1-back was more challenging than the auditory n-back tasks used in previous chapters, because it required a response on almost every trial (and continuous updating of working memory). There was a short practice block of 11 trials (2 blank trials) followed by a test block of 76 trials (69 number trials and 7 blank trials). Initially, we included a second test block of 2-back trials, but the older adult participants found the task too challenging to complete, with very few responses captured. Both accuracy (ACC: %) and reaction times (RT: ms) were recorded logged in E-Prime.

5.2.4.5 Stroop task

A congruent/incongruent judgment Stroop task (word-colour stimuli: Stroop, 1935) was administered to assess executive sustained attention, conflict monitoring and response adaptation/switching (Zurrón et al., 2014; Zurrón, Pouso, Lindín, Galdo, & Díaz, 2009). This task visually presented the words “RED”, “GREEN”, “YELLOW” and “BLUE” in either their congruent font colour (“RED” in red type) or an incongruent colour (“RED” in blue type). There were 2 blocks of 102 trials, each with 90 congruent and 12 incongruent trials presented in random order (with a short break between blocks). The words were presented in the centre of the screen on a black background for 1300ms, with

a 350ms inter-trial blank screen. Participants were required to make a judgment and response on each trial by quickly pressing the left mouse button when the trial was congruent and the right mouse button for an incongruent trial. There were four dependent variables for analysis: congruent and incongruent accuracy (ACC: %), and congruent and incongruent response times (RTs: ms).

5.2.5 EEG Data Recording

Details of the electrophysiological setup, EEG data recording, and EEG/ERP data processing is provided in Chapter 2 (section 2.3.4, and 2.3.5). ERP segmentations time-locked to stimulus onset were set and averaged using Brain Electrical Source Analysis software (BESA version 5.3; GmbH, Germany). ERP epoch length was set at -200 to 1,000ms, with a -200 to 0ms pre-stimulus baseline correction interval. Event-related potential (ERP) components were identified and defined based on visual-inspection of the grand average waveforms and previous literature (Gajewski & Falkenstein, 2014; Killikelly & Szucs, 2013; Mager et al., 2007; Zurrón et al., 2014). Different electrode positions were analysed due to different scalp distributions for the respective components. Grand averages for all participants and participant groups were calculated separately for each task, and mean amplitudes and latencies acted as the dependent variables for all statistical comparisons. Early sensory ERP components (P1, N1, and P2) were preliminarily compared across conditions and groups. Analysis of later EF-related components (N2, P3) on the n-back and Stroop task were of particular interest, and this analysis was carried out with planned comparisons between the two older groups (older fallers and older non-fallers).

5.2.6 Procedure

After obtaining informed written consent, participants completed all control measures, followed by 2 SSWS gait analysis trials, and the 3 seated computer-based tasks with concurrent electrophysiological recording of scalp-related potentials. The EEG set-up protocol is detailed in Chapter 2 (section 2.3.4). All tasks were completed in one session lasting approximately 2 hours (with breaks offered to participants between gait analysis, EEG cap and electrode application, and neuropsychological testing). Participants were thanked for their time and debriefed at the end of the experiment session.

5.2.7 Statistical analysis

A MANOVA was used to compare the groups of the three NART predicted IQ scores, with one-way ANOVAs and t-tests used to compare the groups on height, FES-I, MMSE and MoCA scores. A series of one-way ANOVAs compared the groups on each of the gait characteristic variables. Cognitive variables and ERP components were analysed across task conditions and between groups using one-way or mixed factorial ANOVAs between and within the groups. Seven participants did not complete the Stroop task (3 Young, 3 ONF and 1 OF adult): some participants reported that they found the task too challenging and did not wish to continue, in other cases there were some technological/data recording issues. Comparisons between fallers and non-fallers were of particular interest on cognitive measures and their associated ERP components. In all cases, Levene's test of homogeneity of variances and Mauchly's test of sphericity were used, and the Greenhouse-Geisser correction was applied for violations of sphericity. Bonferroni-corrected alpha values were used where multiple comparisons were made.

5.3 Results

5.3.1 Group comparisons

One way ANOVA comparisons showed no significant differences between the young, ONF and OF groups in height ($F(2, 34) = 1.64$, $p = .21$) or FES-I score ($F(2, 38) = 0.23$, $p = .80$). All groups had an FES-I score indicating moderate concern about falling (Delbaere et al., 2010). A MANOVA compared the 3 groups on the 3 NART IQ performances and found no main effect for group [$F(2, 38) = 0.301$, $p = .742$], and no interaction effect ($F(2.83, 53.70) = 0.51$, $p = .670$). There were no differences in MMSE scores (all > 28) between OF ($M = 29.50$, $SEM = 0.27$) and ONF ($M = 29.00$, $SEM = 0.32$); $t(19) = 1.09$, $p = .29$. MOCA scores (all > 23) also did not differ between OF ($M = 27.13$, $SEM = 0.79$) and ONF ($M = 26.39$, $SEM = 0.74$); $t(19) = 0.66$, $p = .52$. See Table 5.1 for all control measure values.

Table 5.1. *Mean and SEM values for the NART predicted IQ scores, height (cm), FES-I scores, MMSE and MoCA scores in the young, older non-faller (ONF) and older faller (OF) groups.*

Control Measure	**Young**	**ONF**	**OF**
NART Full Scale IQ	113.25 (1.24)	113.54 (3.56)	116.00 (2.40)
NART Verbal IQ	111.40 (1.16)	111.38 (3.27)	113.88 (2.24)
NART Performance IQ	112.35 (1.11)	112.54 (3.17)	114.75 (2.19)
Height (cm)	172.33 (2.47)	165.00 (4.08)	171.71 (2.75)
FES-I	21.35 (1.19)	22.31 (1.68)	20.63 (2.22)
MMSE	-	29.00 (0.32)	29.50 (0.27)
MoCA	-	26.38 (0.74)	27.13 (0.79)

5.3.2 Gait Analysis

The mean (*M*) and standard error of the mean (*SEM*) values for all gait variables are presented in Table 5.2. There were no significant differences between the 3 groups (young, ONF and OF) on any of the normal walking gait characteristics: speed [$F(2, 38) = 0.60$, $p = .554$]; stride time [$F(2, 38) = 0.72$, $p = .494$]; CV stride time [$F(2, 38) = 0.89$, $p = .420$]; stride length [$F(2, 38) = 0.37$, $p = .690$]; or CV stride length [$F(2, 38) = 0.29$, $p = .747$]. For this reason, normal walking gait characteristics were not directly correlated with cognitive performances and ERPs.

Table 5.2. *Mean and SEM values for speed, stride time, CV stride time, stride length and CV stride length values for the young, older non-faller (ONF) and older faller (OF) groups.*

Gait Measure	**Young**	**ONF**	**OF**
Speed (m/s)	1.19 (0.02)	1.23 (0.03)	1.21 (0.04)
Stride Time (s)	0.95 (0.14)	0.91 (0.03)	0.95 (0.03)
CV Stride Time (%)	7.42 (0.31)	6.82 (0.30)	7.10 (0.43)
Stride Length (m)	1.13 (0.02)	1.11 (0.25)	1.14 (0.03)
CV Stride Length (%)	49.30 (0.81)	48.37 (0.83)	49.25 (1.50)

5.3.3 Behavioural and Electrophysiology data

Motor task RT, n-back accuracy and RT, and Stroop accuracy and RT (on congruent and incongruent trials) were analyzed between the groups. The *M* (and *SEM*) accuracy and response times (RTs) for the cognitive tasks for all groups are presented in Table 5.3.

Concurrent ERPs were identified for each task and compared between the groups and across conditions (where relevant). Differences between ONF and OF were of particular interest for addressing this study's aims.

Table 5.3. *Mean* (*and SEM) cognitive task accuracy (ACC) and reaction time (RT) values for the young, older non-faller (ONF) and older faller (OF) groups.*

Cognitive Task	**Young**	**ONF**	**OF**	***p < .05 **p < .01**
Motor RT (ms)	225.64 (11.98)	363.63 (64.98)	296.30 (41.75)	*Y < ONF
1-back ACC (%)	98.85 (0.36)	76.75 (4.62)	61.84 (12.77)	**Y > ONF/OF
1-back correct RT (ms)	474.10 (30.54)	926.82 (51.79)	1036.36 (61.02)	**Y < ONF/OF
1-back error RT (ms)	818.70 (160.74)	304.08 (65.41)	412.45 (100.71)	**Y > ONF
Stroop Congruent ACC (%)	99.21 (0.23)	98.76 (0.39)	96.95 (1.24)	*Y > OF
Stroop Incongruent ACC (%)	91.18 (2.50)	71.67 (6.80)	84.03 (3.30)	**Y > ONF
Stroop Congruent RT (ms)	615.87 (19.13)	671.10 (19.88)	735.96 (46.67)	*Y < OF
Stroop Incongruent RT (ms)	736.60 (19.91)	945.25 (39.22)	955.78 (50.87)	**Y < ONF/OF

5.3.3.1 Motor Task

On the Motor task, there was a main effect for group on RTs (see Table 5.3): $F(2, 38) = 3.56$, $p = .038$, $\eta^2 = 0.16$. *Post hoc* tests using the Bonferroni correction revealed that the younger group responded significantly faster ($M = 225.64$, $SEM = 11.98$) than the ONF group ($M = 363.63$, $SEM = 64.98$): $p = .035$. The Motor task showed clear N1-P2 auditory

evoked-potential (AEP) components that were observable following presentation of the auditory stimulus. One-way between groups ANOVAs were carried out for N1 and P2 mean amplitude and peak latency at left posterior channel P7. N1 peaks were maximal between 95ms–160ms post-stimulus. There were no significant differences between the young, ONF and OF groups in N1 amplitude [$F(2, 38) = 1.24$, $p = .30$, $\eta 2 = 0.06$] or latency [$F(2, 38) = 0.72$, $p = .492$, $\eta 2 = 0.04$]. The P2 component peak was defined between 160ms –250ms post-stimulus. There was a large main effect of group for P2 amplitude at P8; $F(2, 38) = 4.9$, $p = .013$, $\eta 2 = 0.21$ (see Figure 5.1). *Post hoc* tests revealed a larger mean amplitude for the ONF group ($M = 4.06$, $SEM = 0.72$) than the younger group ($M = 1.92$, $SEM = 0.33$): $p = .013$. However, there were no group differences in P2 latency at P7: $F(2, 38) = 1.24$, $p = .30$, $\eta 2 = 0.65$.

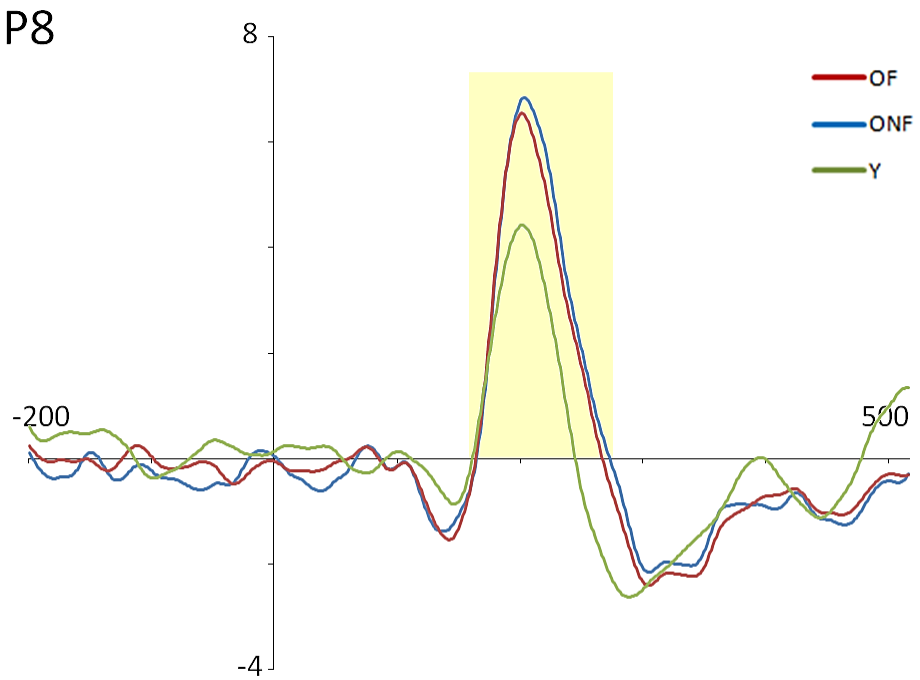

Figure 5.1. *Motor task P2 component rising between 160ms –250ms post-stimulus at channel P8 for young (green), older non-faller (blue) and older faller (red) groups, measured in microvolts (mV: y-axis) over time (ms: x-axis). On average, 99.95% of trials were accepted for this task.*

5.3.3.2 1-back Task

An age-related effect between the groups was also observed for 1-back accuracy: $F(2, 31)$ 14.20, $p < .001$, $\eta^2 = 0.48$, with the younger group performing more accurately (M = 98.85, SEM = 0.36) than both the ONF (M = 76.75, SEM = 4.62, p = .003) and OF groups (M = 61.84, SEM = 12.77, $p < .001$). For RTs, a mixed factorial 3 (groups) x 2 (response accuracy: correct/error) ANOVA showed a significant main effect of response accuracy (F (1, 17) = 22.57, $p < .001$, $\eta^2 = 0.57$), and a response x group interaction effect (F(2, 17) = 26.24, $p < .001$, η^2p = 0.76.) whereby the young group had significantly faster reactions times (M = 474.1, SEM = 30.54) when responding correctly than the ONF (M = 926.82, SEM = 51.79) and OF groups (M = 1036.36, SEM = 61.02); all $p < .001$. However, when responding incorrectly (error), the young group had significantly slower reaction times (M = 818.7, SEM = 160.74) than the ONF group alone (M = 304.08, SEM = 65.41): p = .006, η^2p = 0.45.

Three clear ERP components–P1, N2 and P3a–were observed in response to the visual stimulus on the 1-back task. One way ANOVAs were carried out between the groups on correct response trials. The P1 was most prominent at occipital electrode O1, occurring between 100ms and 195ms. There was no effect of group on P1 amplitude [F(2, 31) = 3.14, p = .462, η2 = 0.049]. However, there was for peak latency, F(2, 31) = 7.83, p = .002, η2 = 0.36, where P1 latency for the ONF (M = 130.60, SEM = 4.66) and OF group (M =119.63, SEM = 6.17) occurred significantly earlier than for the younger group (M = 155.09, SEM = 6.53). The N2 peak was maximal between 150ms and 260ms post stimulus, and was largest over posterior lead P7. There were no significant differences between the groups in mean amplitude [F(1, 32) = 0.276, p = .603, η2 = 0.009] or latency [F(2, 31) = 1.26, p = .299, η2 = 0.074]. The 1-back P3a was maximal at right

posterior PO4 between 230ms and 430ms, and also revealed no significant group differences in mean amplitude or latency [amplitude: $F(2, 31) = 1.19$, $p = .319$, $\eta 2 = 0.071$; latency: $F(2, 31) = 1.45$, $p = .251$, $\eta 2 = 0.085$].

5.3.3.3 Stroop Task

A mixed factorial 3 (groups) x 2 (trial: congruent and incongruent) ANOVA for Stroop task accuracy revealed a significant main effect of trial [F (1, 29) = 37.89, $p < .001$, $\eta^2 p = 0.566$] and a trial x group interaction [F (2, 29) = 4.47, $p = .02$, $\eta^2 p = 0.235$], as well as a main effect of group; F (2, 29) = 4.27, $p = .024$, $\eta 2p = .228$). Follow-up analyses showed that on congruent trials, young adults (M = 99.21, SEM = 0.23) are more accurate than OF adults (M = 96.95, SEM = 1.24): $p = .015$: whereas, on incongruent trials, younger adults are significantly more accurate (M = 91.18, SEM = 2.50) than ONF (M = 71.67, SEM = 6.80): $p = .006$. These age-related differences were also reflected in the RT values. Younger adults were significantly faster at responding accurately on congruent trials (M = 615.87, SEM = 19.13) than the OF adults (M = 735.96, SEM = 46.67): $p = .011$. For incongruent trials, young adults were faster (M = 736.60, SEM = 19.91) at responding accurately than both the ONF (M = 945.25, SEM = 39.22) and OF adults (M = 955.78, SEM = 50.87); all $p < .001$.

Early P1 and N2 components were observable at posterior sites in response to the visual stimuli on the Stroop task. These were followed by a positive waveform in a latency range of 200-385ms. Repeated measures ANOVAs were conducted to investigate the effect of group (young, ONF, OF) and trial condition (congruent or incongruent) on mean amplitude and latency. The P1 component recorded at occipital electrode O2, occurring between 95ms-205ms, showed no significant main effect of group [$F(2, 32) = 1.64$, $p = .210$, $\eta^2 p = 0.093$], or interaction effect on mean amplitude [$F(2, 32) =$

2.85, p = .073, η2 = 0.151]. There was a main effect of group on peak latency however [F(1, 32) = 5.92, p = .007, η^2p = 0.27], wherein the younger group (M = 145.43, SEM = 3.75) showed a significantly later P1 latency than the ONF group (M = 126.77, SEM = 4.66) on congruent trials.

N2 mean amplitude and peak latency at channel O1 (from 145ms-210ms) exhibited a main effect of trial condition (F(1, 32) = 7.45, p = 0.01, η^2p = 0.189) and group (F(2, 32) = 7.45, p = 0.002, η^2p = 0.318). There was no interaction effect between group and trial condition [F(2, 32) = 0.75, p = 0.48, η^2p = 0.045]. Congruent trials (M = -3.70, SEM = 0.61) elicited greater N2 amplitude at O1 than incongruent trials overall (M = -2.86, SEM = 0.63, p = .01), with the ONF group displaying a significantly larger N2 components (p = .002) on both trial types (M = -5.47, SEM = 1.01) compared to the younger group (M = -.62, SEM = 0.81). See Figure 5.2 below. No significant effects were found for N2 latency at O1: trial condition: [F(1, 32) = 2.37, p = .134, η^2p = 0.069]; group: [F(2, 32) = 3.41, p = 0.46, η^2p = 0.176], interaction: [F(2, 32) = 0.74, p = .486, η^2p = 0.044].

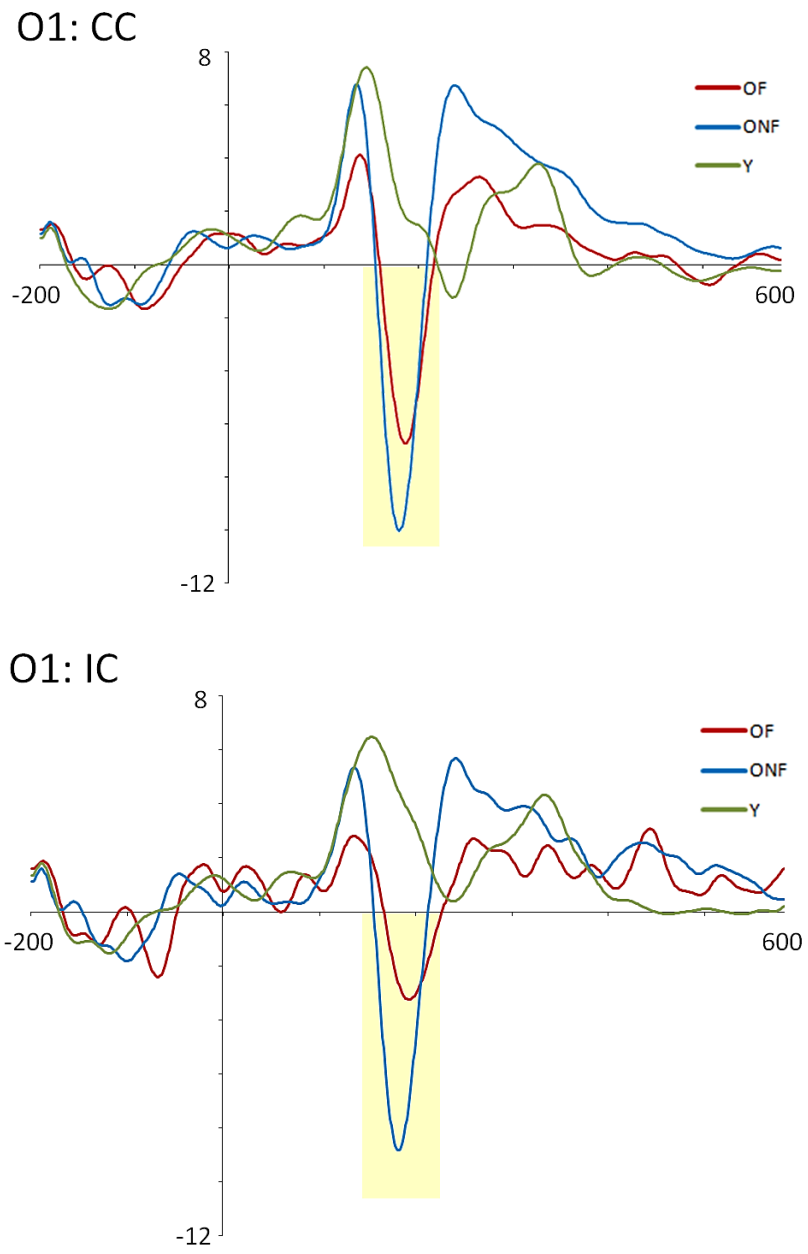

Figure 5.2. *Stroop task N2 potential recorded at occipital electrode O1 for young (green), older non-faller (blue) and older faller (red) groups on congruent correct (CC: left panel) and incongruent correct (IC: right panel) trials, measured in microvolts (mV: y-axis) over time (ms: x-axis). On average, only 0.15% of trials were rejected for the CC condition, and only 0.13% rejected for the IC condition.*

We only identified one later positivity after the N2, presenting at midline Pz and Oz between 200-385ms post stimulus for both the Younger and ONF groups (but not the OF). This component was considered to be an early P3a-like component, based on similar

windows and sites reported recently on an equivalent Stroop judgment task (Zurrón et al., 2009; Zurrón et al., 2014; Killikelly & Szucs, 2013; Mager et al, 2007). Zurrón et al., found a "first P3" amplitude over site Pz, and a P3b component measured at Fz, Cz and Pz in the window of 360-430ms. Here, we saw the greatest amplitude over site Pz and Oz in a time frame more consistent with a first P3 or P3a as we have termed it here. While previous studies have defined the P3a within the window of 300-450ms post stimulus (Eppinger, Kray, Mecklinger, & John, 2007), more recent investigations of Stroop-related ERPs in young and older adults investigate earlier windows: Killikelly & Szűcs (2013) analyzed an early P3 peak as early as 180-230ms in young adults, and 250-335ms in comparable middle aged/older adults).

A repeated measures ANOVA revealed a main effect of group for this early P3 peak; $F(2, 31) = 4.88$, $p = .014$, $\eta^2 p = 0.24$. Planned comparisons between the ONF and OF groups revealed a significantly greater peak amplitude for the ONF group on congruent trials at both Pz (OF: $M = 0.23$, $SEM = 0.14$; ONF: $M = 1.39$, $SEM = 0.28$; $p = .01$) and Oz (OF = $M = 0.36$, $SEM = 0.50$; ONF: $M = 3.41$, $SEM = 0.81$; $p = .013$). Peak amplitude was also greater for ONF ($M = 2.71$, $SEM = 0.81$) than OF ($M = 0.18$, $SEM = 0.49$) on incongruent trials at Oz ($p = .035$). Figure 5.3 illustrates this suggested early P3 (P3a) waveform at Pz and Oz, with Oz scalp topographies at the ONF peak amplitude (congruent: 229ms; incongruent: 234ms). There was no main effect for group on P3a latency: $F(2, 32) = .42$, $p = .66$.

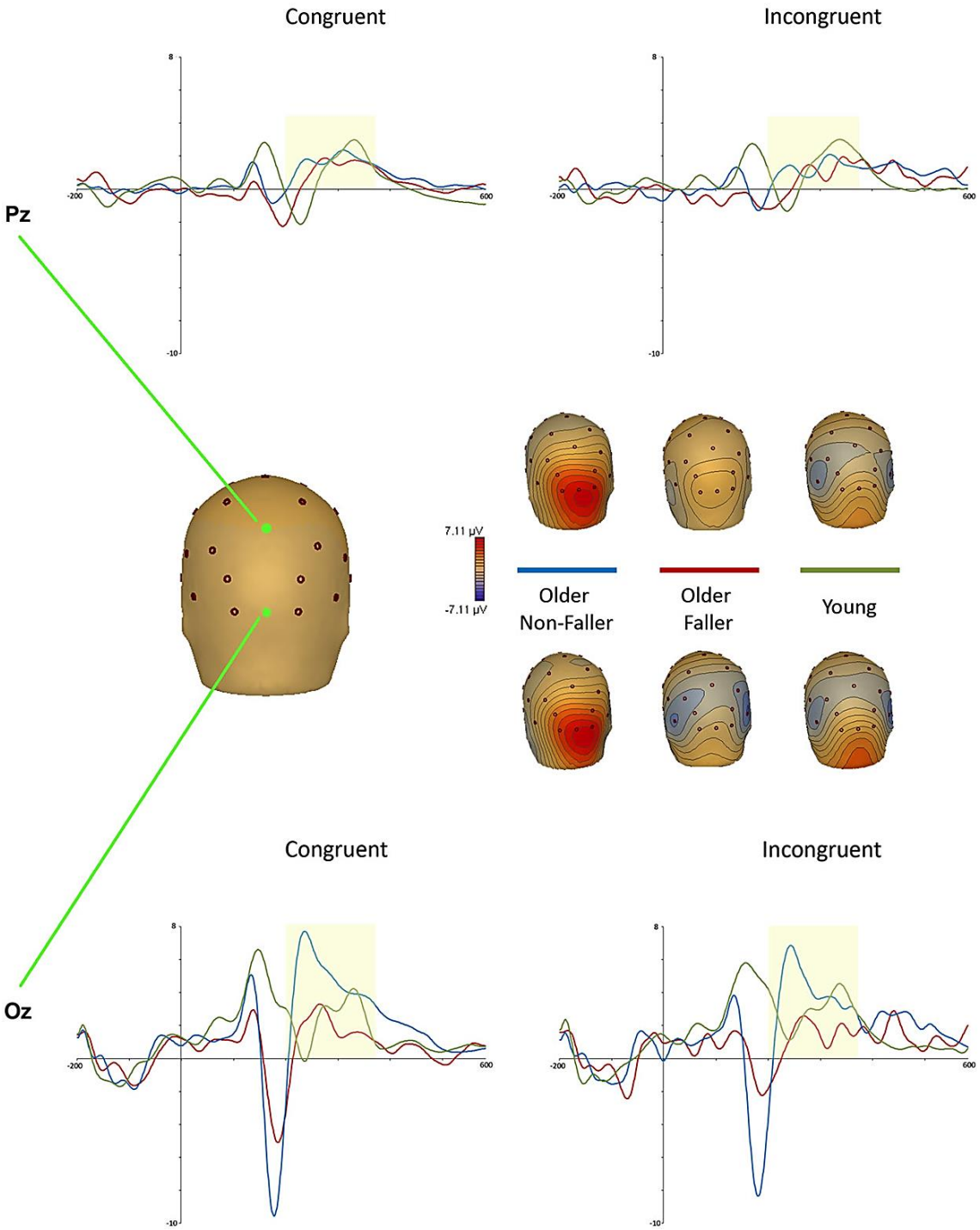

Figure 5.3. *Stroop task P3a event-related potentials (ERPs) recorded at midline and occipital electrodes Pz (top) and Oz (bottom) for young (green), older non-faller (blue) and older faller (red) groups for congruent and incongruent trials. ERP is measured in microvolts (mV: y-axis) over time (ms: x-axis). Scalp topographies for maximal P3a amplitude on congruent trials (at 229 ms) and incongruent trials (at 234 ms) are shown for each group. On average, only 0.15% of trials were rejected for the CC condition, and only 0.13% rejected for the IC condition.*

5.4 Discussion

This experiment sought to identify the EF-associated EEG neural activity underlying gait impairments and falls in older adults. The groups were matched on all control measures, including FES-I scores (indicating the younger adults were as concerned about falls as the older adults). The behavioural results reveal some ageing-related effects on cognitive task responses, suggesting that older adults are generally less accurate, and respond more slowly, than young adults on these measures of cognitive performance: this age-related trend is to be expected. Although there are no clear differences between the ONF and OF groups, there are subtle differences: e.g. the young group perform better than the OF on congruent trials (in ACC and RT), but on incongruent trials, the young perform better than the ONF on accuracy, and better than both older groups on RTs (see Table 5.3 above).

We hypothesized differences in quantitative gait speed, stride time and stride time variability during normal (single-task) walking between the older adult fallers and older adult non-fallers. However, we were unable to identify any significant differences in gait characteristics between any groups on this normal walking task. As we recruited healthy community-dwelling older adults who were screened for any neurological, psychological or musculoskeletal impairments, the two main intrinsic risk factors for falls were age and experience of a first fall (WHO report: Skelton & Todd, 2004).

As with the last chapter, our older adult samples were relatively healthy and active individuals (volunteering from the community and community groups), with comparatively young mean ages (ONF M = 70.83, OF M = 63.75) compared to the samples reported in other studies. However, it is of note that the older fallers had a younger mean age than the older non-fallers. This idiopathic young sample, and the simple demands of the straight walkway gait assessment (walking without any distraction, allowing for full attention to be dedicated to the task), may account for the homogeneity

between the groups on measures of gait. It may the case that the OF group has learned to compensate for deficits, and in the absence of a challenging pathway or dual-task load, were able to perform comparatively well compared to the non-faller group. This finding is in line with others who have failed to find differences in spatiotemporal gait between fallers and non-fallers on baseline straight path walking gait (Mirelman et al., 2012; Terrier & Reynard, 2015). A more challenging pathway for normal walking (with obstacles and turning), or the use of dual-tasks, may be necessary to identify fall-related gait differences within healthy, active older adult samples.

Due to the absence of group differences in normal walking gait performance, a correlation between seated EF performances and gait metrics (e.g. speed) was not conducted. Some age-related differences in n-back and Stroop accuracy and reaction times were observed, which were reflected in some ERP amplitude and latency differences (which is not surprising). However, there were no significant behavioural differences between the older adult groups that could relate to fall-status. This is in contrast to the findings of Buracchio et al. (2011) and Springer et al. (2006), in which EF performance was linked with falls and predictive of DT performance. Our findings could be due to the smaller number of participants in the ONF and OF groups. However, further investigation is needed to assess the validity of cognitive-task screening for falls in older adults without obvious gait impairment (such as the idiopathic older fallers in this experiment exhibiting comparable normal walking gait performances to young adults).

Despite the lack of differences in behavioural results, there were interesting group differences at the putative early P3a-like peak on the Stroop task. Only the young and ONF groups exhibited a positivity peak after the N2 over parieto-occipital sites, with no further components present for the OF group (Figure 5.3). While it should be noted that the task was largely visually-based, with stimuli which would elicit strong activation over

occipital and parietal areas, there is disparity between the positivity reported here and the previous literature defining Stroop P3 components: age-related P3a components have previously been evident at more frontocentral electrode sites (Fz, Cz), with a more posterior P3b component (not evident here) commonly associated with EF Stroop task processing (Killikelly & Szűcs, 2013; Zurrón et al., 2014). This positivity also presented quite early in comparison to reviews of P3 component windows (Eppinger et al., 2007; Polich, 2007), but was comparable to earlier windows recently reported recently by Killikelly and Szűcs (2013) in young and older adults. As we did not find any significant differences in the latencies of this component between the groups, we considered the amplitude difference may be attributable to the group fall-status.

Despite the somewhat irregular nature in comparison to previous literature, we consider this post-N2 positivity to belong to the EF-related P3 component. Luck (2014) argues that ERP components should not be solely defined by their superficial characteristics (latency, scalp distribution and polarity), but rather by the underlying computational operation and neuroanatomy. Considering this, an ERP component may occur at different latencies and sites, but still reflect the associated functional processes. Although this P3a was maximal at midline and occipital electrode sites Pz and Oz, previous functional Magnetic Resonance (fMRI) and EEG studies have posited a frontal generator for the P3a component (McCarthy, Luby, Gore, & Goldman-Rakic, 1997; Polich, 2007). Neuroimaging and combined fMRI-ERP studies have evidenced interactive activity in frontal PFC, dorsolateral PFC, and ACC areas, and the PPC, in top-down cognitive allocation for the detection of sensory conflict and behavioural response conflict resolution in Stroop conditions (Kim, Chung, & Kim, 2010; Kim, Johnson, & Gold, 2013; Liston, Matalon, Hare, Davidson, & Casey, 2006; Tang, Hu, Li, Zhang, & Chen, 2013). More recently, focus has been directed to the neural connectivity networks,

rather than specific brain regions, underlying Stroop conflict processing. This work demonstrates PPC related higher connectivity within the central executive network (CEN), and lower intra-semantic network (SN) connectivity that positively predicts conflict adaptation via top-down cognitive control (Wang et al., 2015).

A comprehensive review of the P300, P3a and P3b components by Polich (2007) states that P3a generation is considered to occur when adequate attentional focus is applied to the stimulus. After initial sensory processing, attentive stimulus-comparison processing evaluates the stimulus in relation to the previous event in working memory. The potential P3a exhibited in our data by the ONF group was present on both congruent and incongruent trials, likely due to the manual response and congruent/incongruent judgment Stroop task utilized (requiring conflict monitoring and response resolution on each trial). This positivity may reflect frontally-driven attentional responding to the stimulus, or increased top-down CEN connectivity, allowing for the resolution of stimulus-conflict and the appropriate response for congruent and incongruent trials to be determined (Park & Reuter-Lorenz, 2009; Polich, 2007; Wang et al., 2015). There is also the possibility that this amplitude represents a P3b component, normally implicated in uncertainty when making decisions in response to the stimulus. However, the time window we observed this component at was more consistent with the earlier P3 windows reported previously (Zurron et al., 2009).

Additionally, this potential P3a, occurring in our fall-free older group could reflect the adaptive and plastic neural compensation associated with successful ageing in healthy older adults (in accordance with the scaffolding theory of ageing: Park & Reuter-Lorenz, 2009). It is possible that this difference between the groups underlies, or at least contributes to, their respective fall-status. However, the absence of cognitive performance differences in this study requires further investigation to better elucidate the link between

gait, cognitive performance and the scalp-recorded ERPs associated with top-down control in older adult fallers and non-fallers. Possibly a dual-task condition would have been challenging enough to reveal top-down cognitive and gait control impairments in the fallers in line with the ERP findings.

Further analysis focusing on the P3 over frontal areas should be pursued with a larger sample of fallers and non-fallers to specifically examine a potential fall-related lack of frontal attention and/or neural compensation. The possibility of identifying key neuropsychological impairments in fallers which may be reflected in scalp-recorded neural activity not only advances our understanding of falls, but opens an avenue to the application of alternate neurocognitive screening tools in the applied clinical setting. Research investigating cognitive training has recently shown that practice on a Stroop task resulted in increased *f*MRI-recorded neural activity in the ACC, left inferior parietal lobule, and left dorso-lateral PFC in a modified reading span test targeting attention-switching and conflict resolution between relevant and irrelevant stimuli (Osaka, Yaoi, Otsuka, Katsuhara, & Osaka, 2012). Better understanding of the key executive processes underlying gait and falls could also lead to potential rehabilitative cognitive training in older adults and high fall-risk clinical samples.

5.4.1 Conclusion

This approach may provide tentative evidence of an EF-related ERP component marker of falls. There is a need for further research to comparatively investigate the specific executive processes underlying gait in fallers and non-fallers, with advanced investigation of the related neuroelectric activity. Furthermore, the use of neuroimaging and physiological recording techniques will not only aid in clarifying the cognitive processes at play, but could also translate to the clinical setting for neural screening of fall risk in

older adults and clinical samples (e.g. identifying increased fall-risk in stroke survivors after the motor recovery plateau). This is investigated in the next chapter.

Chapter 6

Investigating cognitive, electrophysiological and dual-task markers of gait impairment, following stroke.

Abstract

Falls are a common problem for stroke survivors in both acute and chronic stages of recovery (Batchelor, Mackintosh, Said, & Hill, 2012). Dual-task research has evidenced the role of attention and other higher-level processes mediating control of gait post-stroke, yet clinically, the role of cognition in gait and fall-risk after stroke has been largely overlooked (Campbell & Matthews, 2010). This chapter presents a study investigating potential dual-task, cognitive and electrophysiological markers of gait impairment and fall-risk post stroke. We compared cognitive-motor interference effects on a working memory (2-back) and sustained-attention/response conflict (Stroop) task in stroke survivors (n = 11) and age-matched healthy control participants (n = 13). Seated cognitive performances were also recorded with concurrent electrophysiological recordings of event-related potentials. We did not find significant differences between older adult controls and stroke survivors in any gait or cognitive measures, or the associated ERPs. Therefore, we were unable to identify any dual-task, cognitive or electrophysiological biomarkers of fall-risk post-stroke. This may be due to our sample of relatively healthy older adults and well-recovered stroke survivors, who may not have to compensate much to maintain gait control while dual-tasking on a straight walkway (without obstacles). Future studies suggesting the use of more taxing gait tasks, comparing fallers and non-fallers, and monitoring the recovery of gait and cognitive functions as well as dual-task capability post-stroke are all discussed.

6.1 Introduction

Falls are a common problem for stroke survivors in both acute and chronic stages of recovery (Batchelor et al., 2012). Previous research estimates as many as 23-62% of survivors experience at least one fall post-stroke (Langhorne et al., 2000; Lim, Jung, Kim, & Paik, 2012), including one study of Dublin-based stroke patients in Ireland which found 23.5% had experienced at least one fall post-stroke (Callaly et al., 2015). Other studies of stroke-survivors post-discharge from rehabilitation (6+ months post-stroke) found that up to 73% fall at least once (Forster & Young, 1995; Mackintosh, Goldie, & Hill, 2005), and that falls occur most often while ambulating (Dorit Hyndman, Ashburn, & Stack, 2002). These incidence rates of falls in long-term survivors of stroke are also higher than in matched community older adult controls (Jorgensen & Jacosen, 2002; Simpson, Miller, & Eng, 2011).

Generally, falls in older adults and stroke survivors can result in severe physical injuries (such as hip fracture), psychosocial consequences (fear of falling and social isolation), loss of dependence and even mortality (HSE, 2008; Stel, Smit, Pluijm, & Lips, 2004; Weerdesteyn, de Niet, van Duijnhoven, & Geurts, 2008). However, falls post-stroke can also have huge detrimental set-backs in terms of cognitive and motor recovery, including increased hospital stays of up to an additional 11 days (Teasell, McRae, Foley, & Bhardwaj, 2002; Wong, Brooks, Inness, & Mansfield, 2016). In particular, patients experiencing falls and fall-injuries post-stroke have high morbidity and mortality rates (Divani, Vazquez, Barrett, Asadollahi, & Luft, 2009; Langhorne et al., 2000), and also place a heavy burden on health care services and the state (Evers et al., 2004). As such, recovery of gait post-stroke is a priority, particularly for the patient's functional remediation and return to the activities of daily living (Belda-Lois et al., 2011).

Gait patterns can vary widely post-stroke, but they are most often characterised by a slower gait speed (Weerdesteyn et al., 2008). Post-stroke gait speeds ranging from 0.23–0.73 m/s on average, or 0.78-0.95 m/s in higher-functioning stroke survivors (Beyaert, Vasa, & Frykberg, 2015; Huitema et al., 2004; Olney & Richards, 1996), are lower than undiagnosed community controls ranging from 1.35-1.44 m/s in an older Irish national cohort (Kenny et al., 2013). While speed is the most commonly used clinical measure of gait impairment post-stroke, inter-limb asymmetry also accounts for some of the variance (particularly with hemiparesis), with some evidence of decreased stride length and cadence that can return to baseline with longer recovery (Jonsdottir et al., 2009; Olney & Richards, 1996; Patterson et al., 2008).

Gait speed often improves over time, with maximal recovery occurring within the first 6 months, after which recovery is assumed to plateau (Cockburn, Haggard, Cock, & Fordham, 2003; Duncan, Goldstein, Matchar, Divine, & Feussner, 1992). However, walking while completing a secondary cognitive task does not improve over time (Cockburn et al., 2003; D Hyndman, Ashburn, Yardley, & Stack, 2006). This indicates that there is an increased role of attention and top-down inputs in post-stroke gait (Weerdesteyn et al., 2008). However, traditional rehabilitation of gait post-stroke mainly targets musculoskeletal function, such as exercise programmes focusing on muscle dysfunction, transfer training and fitness (Beyaert et al., 2015; Eng & Fang Tang, 2007). Yet research shows that the commonly used strength training rehabilitation technique does not directly influence recovery of walking gait: i.e. improved muscle strength does not transfer to improved gait (Eng & Fang Tang, 2007). Meanwhile the role of cognition in gait and fall-risk after stroke has been largely overlooked (Campbell & Matthews, 2010).

Recent work (Duffin et al., 2012) has shown that there are subtle cognitive deficits post-stroke that are not identifiable through general cognitive measures alone: for example the Mini Mental State Examination (MMSE®: Molloy, Alemayehu, & Robert, 1991) and the Montreal Cognitive Assessment (MoCA: Nasreddine et al., 2005) measures of global cognition. Specifically, stroke survivors (between 2-60 days post-stroke) who were unimpaired on MMSE® indices performed worse than controls on more in-depth measures of spatial attention, spatial/relational processing and associative memory (Duffin et al., 2012). These subtle cognitive impairments may contribute to the increased prevalence of fall-risk in stroke survivors, even after there has been substantial sensory and motor recovery. While a clear profile of cognitive deficits has not been identified, it appears that deficits in executive function and slowed processing speed may be key characteristic features of cognitive decline post-stroke (Cumming, Marshall, & Lazar, 2013). The link between cognition and gait has been evidenced in longitudinal and prospective cohort studies, in which gait mobility measures (the Timed Up-and-Go test and Berg Balance Scale; Berg, Maki, Williams, Holliday, & Wood-Dauphinee, 1992; Podsiadlo & Richardson, 1991) are shown to predict risk of cognitive impairment up to one and two years post-stroke event (Ben Assayag et al., 2015; Ursin et al., 2015). Furthermore, the dual-task paradigm has also been utilised to investigate cognitive-motor interference post-stroke.

As discussed in previous chapters, the dual-task paradigm investigates the cognitive-motor link by measuring interference in gait and cognitive performance as a participant walks while concurrently completing a secondary cognitive task (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2008). Previous work in older adults has evidenced dual-task disruption to many aspects of gait, with executive tasks appearing to be key in the control of ageing gait (Dubost et al., 2006; Holtzer et al.,

2007; see also Chapter 4 of this thesis). A similar, but escalated pattern of effects has also been exhibited for gait control post-stroke (Plummer-D'Amato et al., 2008; Smulders, van Swigchem, de Swart, Geurts, & Weerdesteyn, 2012). Dual-task interference has a consistent effect on gait performance, including reduced gait speed, cadence and stride length (Plummer et al., 2013; Plummer-D'Amato et al., 2008), with some studies also reporting interference on dual-task cognitive performance (Plummer et al., 2013). However, it can be difficult to determine whether cognitive-motor interference post-stroke is due to mobility impairments, attentive control, an inability to perform two tasks simultaneously (due to a limited executive/attentional capacity), or all of the above (Dennis et al., 2009). However, a recent systematic review and meta-analysis has also shown that dual-task cognitive-motor interference paradigms can be used as interventions to elicit short-term improvements in gait and stability post-stroke (Wang et al., 2015).

As with the literature on cognitive-motor interference in older adults, a number of problems have been identified that hinder our understanding of the role of cognition in gait control, and its translation to the clinic (D Hyndman et al., 2006). These include the methodological variability in choice of dual-task, the lack of comparative controls in some cases (e.g. Manaf, Justine, Ting, & Latiff, 2014; Plummer-D'Amato et al., 2008), inconsistent analysis of bidirectional effects, and the heterogeneity of stroke (D Hyndman et al., 2006). We attempt to address some of these problems by conducting a dual-task experiment comparing stroke survivors to age-matched healthy older adults on different executive and non-executive tasks in both a seated single-task and walking dual-task condition. Previous work by Manaf et al. (2014) found that both a motor and cognitive concurrent task taxed attentional load, resulting in dual-task interference on gait performance (but failed to include a comparative control group).Few studies have compared explicitly different cognitive dual-tasks, but those that have, reveal distinct

effects for different tasks, positing that the type of task matters for determining cognitive-motor interference on gait post-stroke (Patel & Bhatt, 2014; Plummer-D'Amato et al., 2008).

Understanding the cognitive-motor link is particularly important for our understanding of gait impairments and falls in both older adults and stroke survivors, and for understanding how motor function recovers after the neurological damage of a stroke. Furthermore, this understanding can have important implications for rehabilitation, with some pilot studies already testing the efficacy of training in different cognitive-motor dual-tasks (Plummer, Villalobos, Vayda, Moser, & Johnson, 2014; Plummer-D¿Amato et al., 2012; Plummer-D'Amato et al., 2012; Wang et al., 2015).

Plummer-D'Amato et al. found that a spontaneous speech task affected gait performance more than a working memory (serial subtraction) or visuospatial decision-making (clock) task. However, this study only tested 13 community stroke survivors, without comparison to a control group. Patel and Bhatt (2014) compared 10 chronic stroke survivors to 10 young adults on three dual-tasks, and found that a working memory serial subtraction task had a greater effect on motor performance in stroke patients when compared to a Stroop or visuomotor reaction time task. However, the visuomotor task elicited the greatest cost in cognitive performance in both the chronic stroke survivors and the healthy young adults. Elsewhere, it has been argued that the serial subtraction task does not solely target working memory, but also executive decision making and information updating (Mertens, Gagnon, Coulombe, & Messier, 2006). It is possible that this could account for the increased interference on the subtraction task in Patel and Bhatt's study.

Unlike Patel and Bhatt, we compared survivors 6-18 months post-stroke to age-matched (rather than young) healthy older adults, and investigated the effects of a 2-back

test of working memory, a response-conflict Stroop task and a simple control motor response task on cognitive and motor dual-task performances. We chose the long-validated n-back task of working memory (Owen, McMillan, Laird & Bullmore, 2005) as an alternative to the serial subtraction task, as it constitutes a measure of working memory without the increased load of the subtraction task (that may increase in difficulty/complexity the longer the task goes on). We also investigated seated cognitive performances on these tasks with concurrent electrophysiological recording of event-related potentials, in order to examine any potential association with gait impairments and potential fall-risk. Therefore, we may be able to determine if any dual-task deficits elicited here may be related to subtle cognitive impairments post stroke, as reported previously (Duffin et al., 2012). Few studies have used neuroimaging techniques in this way to examine the neural correlates of dual-task interference in stroke survivors. Stroke events are heterogeneous by nature, however lesion site (left or right) has not been shown to affect dual-task performance in stroke survivors (Haggard, Cockburn, Cock, Fordham, & Wade, 2000; D Hyndman et al., 2006). We seek to identify electrophysiological correlates of impaired executive functioning post-stroke that could act as a marker of fall-risk and gait impairment in stroke survivors.

6.1.1 Aims and Hypotheses

This study investigates the interference effects of explicitly different dual-tasks targeting executive and non-executive domains, on gait and cognitive performances in stroke survivors and age-matched healthy control participants. The overall aim is to identify if dual-task, cognitive or electrophysiological impairments 6+ months post-stroke (after supposed motor recovery plateau) may be related to gait impairments and falls post-stroke. We hypothesis that gait speed will be slower during single-task performance in stroke

survivors, with increased dual-task costs on speed for the executive tasks in comparison to the age-matched control group. We also predict that the executive working memory and response-conflict tasks will cause more interference than the motor task, and that stroke survivors will exhibit subtle cognitive impairments on single-task cognitive performances, in comparison to the older adult controls.

6.2 Methods

6.2.1 Participants

Stroke survivors (SS group) were recruited from Tallaght hospital Stroke Unit hospital records if they were 6-18 months post-stroke and aged 55-85 years. The minimum time post-stroke was set at 6 months, in order to allow for substantial motor recovery: the majority of acute motor recovery takes place in the first 6 months, and plateaus thereafter (Duncan et al., 1992). SS participants were contacted by mail and invited to take part in this study: an invitation letter was accompanied by a *Patient Information Leaflet* detailing the study and what participation would involve, with a copy of the consent form (see Appendix N). Of those who responded to the invitation letters, 11 met the inclusion/exclusion criteria and volunteered to take part (8 male; mean age = 70.91).

All 11 stroke survivor volunteers had a diagnosis of an ischaemic infarct stroke event. We had access to further diagnostic information for 7 of the 11 stroke survivors. Of these, 1 had a posterior stroke syndrome, 2 had anterior stroke syndrome, 1 had lacunar, and 3 had a stroke of unknown aetiology. At discharge, all had a Modified Rankin score (a measure of degree of disability) of less than 2 (low disability): 3 had a score of zero, 2 had a score of two, and 1 survivor's score was unknown. None were identified as having cognitive decline at discharge. The mean time post-stroke was 305.29 days (range 230-438 days), or 10.24 months.

A control group of healthy older adult participants (OA group) aged 55-85 was also recruited from the Maynooth and Tallaght community surrounding areas via flyers and contact with local community groups (n = 13, 4 male; mean age = 68.46). All participants for this experiment were community-dwelling, and only 2 participants in each

group reported a fall in the previous 12 months (see Chapter 2, section 2.1.5 for the operational definition of a fall and detail of the self-report fall history questionnaire).

All participants gave informed written or verbal consent prior to participation, and again at the commencement of testing on the day of their appointment. Exclusion criteria were screened by telephone checklist prior to participation (see Chapter 2, section 2.6, Table 2.2. for OA and SS participant group inclusion and exclusion criteria). This study was conducted in accordance with the Ethical Standards of the American Psychological Association (APA), the Declaration of Helsinki (World Medical Association Inc.), and with the approval of the Maynooth University Ethical committee (see Appendix H) and Tallaght hospital (see Appendix I).

6.2.2 Control Measures

As in previous chapters, the two groups were compared on measures of fear of falling (FES-I: Yardley et al., 2005), premorbid intelligence (National Adult Reading Test: Nelson, 1982), and global cognition (Mini Mental State Examination and the Montreal Cognitive Assessment: Molloy, Alemayehu, & Roberts, 1991; Nasreddine et al., 2005). See Chapter 2, section 2.1 for detailed discussion of each of these measures and how they were carried out. Height (cm), weight (kg) and lower limb strength (5 times sit-to-stand task: Guralnik et al., 2000; Lord, Murray, Chapman, Munro, & Tiedemann, 2002) were also compared across the two groups to ensure the participants post-stroke were not physically different from the control group. The 5 times Sit-to-Stand task is a quick and applicable measure of lower limb strength, and has also been shown to be a predictor of activities of daily living disability in older persons, and a marginal predictor of future falls (Zhang et al., 2013). In this task, participants were asked to sit in a standard height chair with arms crossed over their chest. Participants were then instructed to perform 5

sit-to-stand transfers as quickly and safely as possible when the experimenter said: “go”. The time to complete the 5 transfers was recorded on a stopwatch, and this time is an indicator of lower-limb strength.

6.2.3 Gait Assessment

Participants completed 2 single-task (ST) walking gait trials, and 3 dual-task (DT) walking trials in total. The walkway was a straight 15m path on an open empty corridor. Each trial consisted of walking at a self-selected walking speed (SSWS) along the walkway four times, with an about-turn at each end; this allowed for enough steady-state gait cycles on each pass to analyze normal walking gait outside of start/stop and turn slowing and acceleration. The 2 ST trials of SSWS were averaged to get a better measure of usual (“normal”) walking characteristics. Gait data were recorded and analysed as discussed previously: see Chapter 2, section 2.4. Five gait variables were yielded for analysis: gait speed (m/s); stride time (s); stride time variability (Coefficient of Variability %: CV stride time); stride length (m); and stride length variability (CV stride length %).

6.2.4 Cognitive Tasks

Three auditory response tasks (Motor, n-back and Stroop task) were utilised in both the seated ST cognitive condition and DT walking condition (see details for each below). Each task was generated in E-Prime and run on a Dell Latitude 2.1GHz Intel Pentium Processor laptop. Auditory stimuli (mono 16-bit sound files with a 44.1kHz sampling rate) were presented via wireless fm headphones (Philips), and participants responded as instructed on a hand-held wireless mouse, using their dominant hand index and middle fingers to press the left and right mouse buttons (labelled with the letter “L” and “R”

respectively). Instructions were given verbally at the start of each task, and a practice trial was provided for the n-back and Stroop tasks before test blocks were recorded. For the Motor task, an example of the stimulus was given before commencing the test blocks. The order of the ST and DT conditions was counterbalanced across participants with different stimuli and orders of stimuli in each condition (the Motor and Stroop task stimuli were randomised, and the n-back stimuli were different in each condition). Response accuracy (ACC: %) and response times (RT: ms) were automatically recorded in E-Prime for each task.

6.2.4.1 Motor task

The Motor task–as described in previous chapters–was used as simple stimulus-response attention-demanding control task that does not tax higher-level executive function processing (see Chapter 5, section 5.4.2.1). The only difference in this experiment is that the task consisted of one block of 140 trials and was set to run for 120 seconds in the ST condition, and was manually ended whenever the participant stopped walking at the end of the DT walking condition. Participants had a 1200ms response window from stimulus onset, in which they could respond by clicking the left mouse button.

6.2.4.2 n-back task

An auditory 2-back task–as used in Chapter 4–was employed to assess executive working memory (Owen, McMillan, Laird & Bullmore, 2005). See Chapter 3 section 3.2.3.3 for details of the stimuli. Participants were required to respond by clicking the left mouse button with their dominant index finger, within a 2000ms response window from stimulus onset. In this experiment, the task consisted of 1 practice block of 10 trials (3 target "match" trials), 2 test blocks of 77 trials (with 23 target trials in each block) in the ST

condition, and ran until manually ended by the experimenter upon participant's completion of the walking DT condition.

6.2.4.3 Stroop task

An auditory forced-choice Stroop task was utilised to target sustained attention and response-conflict processing (Shor, 1975; Stroop, 1935). This task consisted of a short practice block of 8 trials (50% incongruent), and 2 test blocks of 52 trials each (50% incongruent) in the ST condition, with a short break offered between each block. For the DT condition, one test block of 100 trials (50% incongruent) ran until the experimenter manually ended the task once the participants had finished walking. There were 4 auditory voice stimuli consisting of the words "high" and "low" played in a high (Hi: 300Hz) or low (Lo: 160Hz) pitch: i.e. "High" in a high pitch ("High"$_{Hi}$), "High" in a low pitch ("High"$_{Lo}$), "Low" in a high pitch ("Low"$_{Hi}$); and "Low" in a low pitch ("Low"$_{Lo}$). Each of the four stimuli occurred on 25% of the trials in a pseudorandom order to ensure no more than 2 consecutive repetitions. Stimuli were presented with a 2000ms response window and with a 300ms inter-trial-interval. There were two response options: a left mouse button click for congruent stimuli ("High"$_{Hi}$ and "Low"$_{Lo}$) and a right mouse button click for incongruent stimuli ("High"$_{Lo}$ and "Low"$_{Hi}$). There were four dependent variables for analysis: congruent and incongruent accuracy (ACC: %), and congruent and incongruent response times (RTs: ms).

6.2.5 EEG/ERP Measurement

Electrophysiological setup, EEG data recording, and EEG/ERP data processing are detailed in Chapter 2 (section 2.3.4, and 2.3.5). Stimulus-locked ERP segmentations were set and averaged using Brain Electrical Source Analysis software (BESA version 5.3;

GmbH, Germany). ERP epoch length was set at -200 to 1,000ms for the Motor task, and -200 to 2,000ms for both the n-back and Stroop task. Event-related potential (ERP) components were identified and defined based on visual-inspection of the grand average waveforms. Grand averages were calculated and the mean amplitudes and latencies were used as the dependent variables for all statistical comparisons. Different electrode positions were analysed based on the respective scalp distributions of each of the components. All identified ERP components were compared across conditions and groups. Analysis of later EF-related components (N2, P3) on the n-back and Stroop tasks were of particular interest.

6.2.6 Procedure

After obtaining informed written consent, participants first completed each of the control measures. Then participants completed the ST and DT walking tasks, and the ST cognitive tasks with EEG/ERP analysis. The order of the cognitive ST and DT conditions was counterbalanced across participants (half of each group completed the seated cognitive ST first). This design allows us to investigate the bi-directional effects of dual-tasking on both cognitive and gait performances, by analysing the dual-task change (DTC %): i.e. the relative change in performance from ST to DT condition (see Chapter 2, section 2.5). No instruction was given regarding which task to prioritise in the DT condition. The concurrent EEG recordings during the cognitive STs also allowed for the investigation of the associated neural correlates of these cognitive performances (the EEG set-up protocol is detailed in Chapter 2, section 2.3.4). All tasks were completed in one session lasting approximately 2 hours in total (with shorts breaks offered to participants between tasks). Participants were debriefed at the end of the session and thanked for their time

6.2.7 Statistical analysis

A MANOVA was used to compare the OA and SS groups of the three NART predicted IQ scores, and independent t-tests were used to compare the two groups on all other control tasks. Cognitive variables (accuracy and RT), the 5 extracted gait variables, and the DTC values for both were analysed between and within the two groups using mixed factorial ANOVAs, with Bonferroni corrected follow-up tests of simple main effects. Changes in performance from ST to DT were investigated using paired samples t-tests. Cognitive task-associated ERPs were also analysed across trial/response conditions (where applicable) and between the OA and SS groups with mixed factorial ANOVAs or independent and paired samples t-tests, as appropriate. Where a low number of error responses were made, only correct responses were of interest in cognitive and ERP measures. A small number of values lying beyond 3 times the interquartile range were removed. Five participants only completed 1 ST walking gait assessment (due to participant fatigue and time restraints); therefore, we could not calculate an average of 2 ST walking trials for these participants. In all cases, Levene's test of homogeneity of variances and Mauchly's test of sphericity were utilised, and the Greenhouse-Geisser correction was applied for violations of sphericity. Where multiple comparisons were made, Bonferroni-corrected alpha values were employed.

6.3 Results

6.3.1 Group comparisons

All mean (*M*) and standard error of the mean (*SEM*) values for each of the control measures are provided in Table 6.1. There were no significant differences between the OA and SS participant groups in mean age, height, weight or lower limb strength (5 times sit-to-stand task) [age: $t(22) = 0.748$, $p = .462$; height $t(22) = 0.193$, $p = .849$; weight: $t(22) = 0.693$, $p = .496$; lower limb strength: $t(22) = 0.668$, $p = .511$]. There were also no differences between the groups on NART scores of intelligence [$F(1, 22) = 0.03$, $p = .858$, $\eta^2p = .001$], fear of falling [FES-I: $t(22) = 0.03$, $p = .998$] or global cognitive performance on the MMSE®-2 [$t(22) = 0.598$, $p = .556$] or MoCA measures [$t(22) = 0.559$, $p = .582$] measures. Both groups had a mean FES-I score indicating moderate concern about balance and falling (Delbaere et al., 2010).

6.3.2 Gait Analysis

The mean and *SEM* values for all gait variables in each of the walking conditions (ST and DT), for both the OA and SS groups, are presented in Table 6.2. The SS group had slower gait speeds on all tasks (see Figure 6.1), but there were no statistically significant differences between the groups or across the tasks this difference was not significant [task type: $F(3, 66) = 0.50$, $p = .684$, $\eta^2p = .022$; group: $F(1, 22) = 1.13$, $p = .299$, $\eta^2p = .049$]. Analysis of each of the other gait variables revealed no significant main effects for task type (ST, Motor DT, n-back DT or Stroop DT), nor any main effects for group, on any of the gait variables: mean stride time [task type: $F(3, 63) = 2.13$, $p = .105$, $\eta^2p = .092$; group: $F(1, 21) = 0.03$, $p = .860$, $\eta^2p = .002$]; CV stride time [task type: $F(1.95, 38.97) = 1.50$, $p = .236$, $\eta^2p = .070$; group: $F(1, 20) = 3.62$, $p = .072$, $\eta^2p = .153$]; mean stride length [task

type: $F(3, 66) = 0.95$, $p = .418$, $\eta^2p = .041$; group: $F(1, 22) = 0.54$, $p = .47$, $\eta^2p = .024$]; and CV stride length [task type: $F(3, 66) = 1.26$, $p = .294$, $\eta^2p = .054$; group: $F(1, 22) = 0.33$, $p = .574$, $\eta^2p = .015$].

Table 6.1. *Mean (and standard error of the mean) values for age, height, weight, 5 times sit-to-stand task performance, the 3 NART-based predicted IQ scores, FES-I scale scores, MMSE® score and MoCA score in both the older adult (OA) and stroke survivors (SS) participant groups.*

	OA	**SS**
Age (years)	68.46 (2.35)	70.91 (2.22)
Height (cm)	166.73 (1.79)	166.05 (3.20)
Weight (kg)	70.51 (3.97)	74.09 (3.06)
5 Times Sit-to-Stand (s)	10.25 (0.62)	11.03 (1.05)
NART Full Scale IQ	109.85 (2.63)	109.27 (2.27)
NART Verbal IQ	108.31 (2.48)	107.55 (2.13)
NART Performance IQ	109.38 (2.37)	108.91 (2.01)
FES-I	23.46 (1.67)	23.45 (1.67)
MMSE®	27.92 (0.60)	28.45 (0.65)
MoCA	24.46 (1.17)	23.55 (1.12)

Table 6.2. *Mean (and standard error of the mean) values for speed, stride time, stride time variability (CV stride time), stride length and stride length variability (CV stride length) for each walking task in the older adult and stroke survivor groups.*

Older Adult Participants

Gait Measure	ST	Motor DT	2-back DT	Stroop DT
Speed (m/s)	1.20 (0.03)	1.17 (0.04)	1.20 (0.03)	1.16 (0.03)
Stride Time (s)	0.93 (0.02)	0.94 (0.02)	0.96 (0.02)	0.97 (0.02)
CV Stride Time (%)	7.28 (0.59)	7.63 (0.71)	6.36 (0.52)	8.10 (1.10)
Stride Length (m)	1.11 (0.01)	1.09 (0.03)	1.15 (0.01)	1.12 (0.02)
CV Stride Length (%)	48.06 (0.91)	46.26 (2.05)	45.38 (1.14)	47.47 (1.63)

Stroke Survivor Participants

Gait Measure	ST	Motor DT	2-back DT	Stroop DT
Speed (m/s)	1.14 (0.03)	1.15 (0.04)	1.14 (0.04)	1.13 (0.04)
Stride Time (s)	0.97 (0.02)	0.97 (0.03)	0.98 (0.03)	0.96 (0.02)
CV Stride Time (%)	6.28 (0.26)	6.13 (0.21)	5.85 (0.23)	6.26 (0.19)
Stride Length (m)	1.10 (0.02)	1.11 (0.02)	1.11 (0.02)	1.11 (0.02)
CV Stride Length (%)	48.34 (1.01)	48.82 (1.72)	47.29 (1.26)	48.06 (1.10)

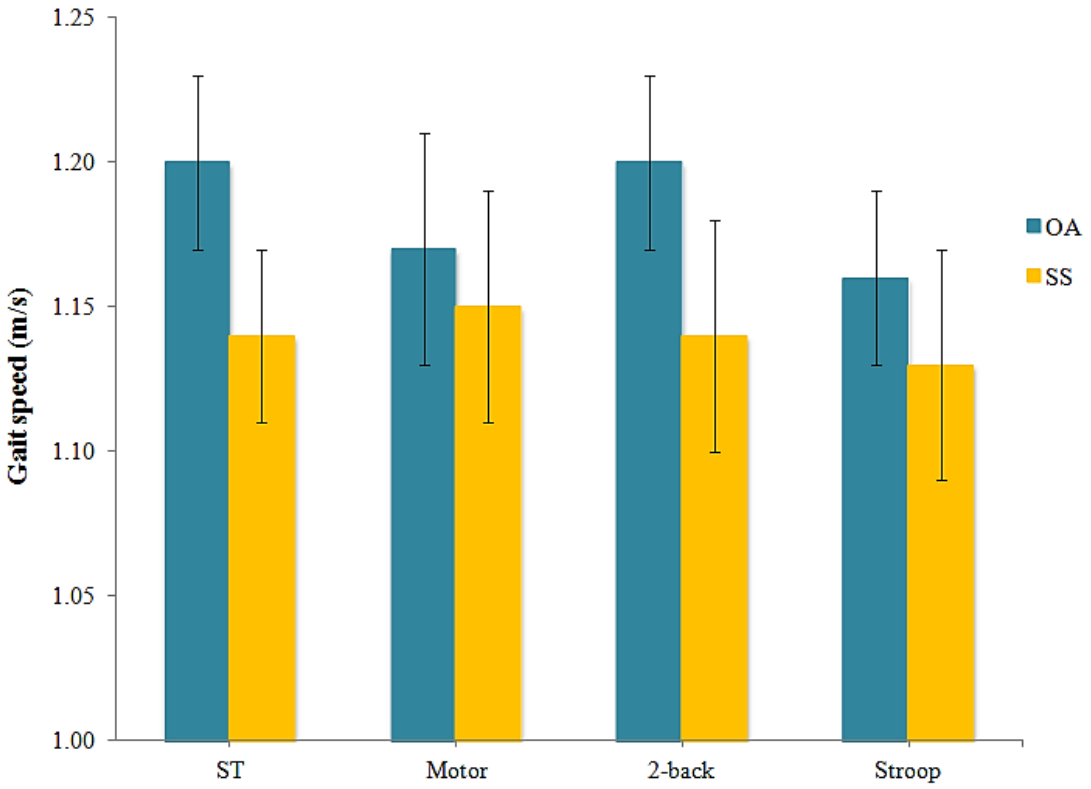

Figure 6.1. *Mean gait speed (m/s: +/- SEM) across single-task (ST) and dual-task (DT) conditions in both the older adult (OA) and stroke survivor (SS) groups.*

6.3.2.1 Gait DTC

DTC (%) values (relative change from ST to DT) for each of the gait variables were compared across task type (Motor, n-back and Stroop task) and between the two groups (OA and SS). The mean (and SEM) gait DTC values for each task type are presented in Table 6.3. There were no main effects for task type or group on speed DTC [task: $F(2, 44) = 0.69$, $p = .508$, $\eta^2p = .030$; group: $F(1, 22) = 0.23$, $p = .640$, $\eta^2p = .010$], CV stride time DTC [task: $F(2, 42) = 3.04$, $p = .059$, $\eta^2p = .126$; group: $F(1, 21) = 1.74$, $p = .201$, $\eta^2p = .077$], mean stride length DTC [task: $F(2, 44) = 1.21$, $p = .308$, $\eta^2p = .052$; group: $F(1, 22) = 0.05$, $p = .834$, $\eta^2p = .002$], or CV stride length DTC [task: $F(2, 44) = 1.54$, $p = .225$, $\eta^2p = .066$; group: $F(1, 22) = 0.02$, $p = .887$, $\eta^2p = .001$]. For mean stride time

DTC, there was a significant main effect for task [$F(2, 40) = 6.30$, $p = .004$, $\eta^2 p = .239$] but no main effect for group [$F(1, 20) = 2.15$, $p = .158$, $\eta^2 p = .097$]. However, follow-up analysis using the Bonferroni correction found no significant differences between the groups (all $t < 1.77$, all $p > .09$), or across the 3 dual-tasks (all $t < 2.38$, all $p > 0.036$: $\alpha = .013$).

Table 6.3. *Motor dual-task change* (*DTC %) values for speed, stride time, stride time variability (CV stride time), stride length and stride length variability (CV stride length) values for each dual-task* (*DT) conditions in the older adult (OA) and stroke survivor (SS) groups. Positive DTC values indicate worse performance on the DT than ST.*

	OA		
Gait DTC	Motor DT	2-back DT	Stroop DT
Speed DTC%	2.06	-0.73	2.34
	(3.47)	(2.98	(3.24)
Stride Time DTC%	1.09	3.57	2.64
	(1.93)	(1.59)	(1.42)
CV Stride Time DTC%	17.32	-4.87	11.43
	(12.02)	(4.15)	(9.41)
Stride Length DTC%	1.43	-3.91	-1.08
	(2.87)	(2.20)	(2.46)
CV Stride Length DTC%	3.25	-5.11	-0.65
	(5.33)	(3.19)	(4.30)
	SS		
Gait DTC	Motor DT	2-back DT	Stroop DT
Speed DTC%	-1.44	-0.58	0.81
	(2.25)	(2.07)	(2.31)
Stride Time DTC%	-0.94	-0.04	-0.11
	(1.19)	(1.18)	(1.04)
CV Stride Time DTC%	-7.64	-8.77	0.26
	(4.55)	(3.01)	(3.85)
Stride Length DTC%	-0.37	-0.44	-1.15
	(1.74)	(1.64)	(2.08)
CV Stride Length DTC%	1.11	-1.72	-0.05
	(3.32)	(3.45)	(3.40)

6.3.3 Cognitive Behavioural Analysis

Motor task RT, n-back ACC and RT, and Stroop ACC (on congruent and incongruent trials) and RT (on congruent correct and incongruent correct trials) were analysed between the groups. Performances on ST and DT conditions were also compared within each group, and the relative DTC was compared between and within the groups across the different tasks. The mean (and *SEM*) values for performances and DTC in performances for each of the cognitive tasks are presented in Table 6.4.

Independent samples t-tests (with Bonferroni correction) revealed no significant differences between the two groups on any of the cognitive performance measures on the Motor, 2-back or Stroop task (all $t < 2.05$, all $p > .052$). When comparing ST to DT performance within the groups, both the OA and SS group were less accurate (OA: $M = 58.17$, $SEM = 1.83$; SS: $M = 59.53$, $SEM = 1.88$) on the 2-back DT in comparison to the ST (OA: $M = 98.70$, $SEM = 0.43$; SS: $M = 98.64$, $SEM = 0.30$): all $t > 19.72$, all $p < .001$. The OA group also had faster RTs when responding correctly on the 2-back DT ($M = 185.89$, $SEM = 14.22$) in comparison to the ST ($M = 227.29$, $SEM = 8.33$): $t(11) = 3.34$, $p = .007$. The same RT trend was observed in the SS group, but the effect was not significant ($p = .08$). See Figure 6.2 for 2-back mean accuracy and reaction time performance in both groups.

Table 6.4. *Mean* (*and SEM) cognitive task accuracy (ACC) and reaction time (RT) values for each cognitive measure in the older adult (OA) and stroke survivor (SS) groups. Positive DTC values indicate worse performance on the DT than the ST.*

	OA			**SS**		
Cognitive Task	ST	DT	DTC%	ST	DT	DTC%
Motor RT (ms)	352.79 (26.19)	332.75 (15.89)	0.00 (10.17)	339.17 (20.68)	393.13 (34.98)	15.91 (7.53)
2-back ACC (%)	98.70 (0.43)	58.17 (1.83)	41.05 (1.88)	98.64 (0.30)	58.36 (2.06)	40.21 (1.88)
2-back correct RT (ms)	227.29 (8.33)	185.65 (13.08)	-20.43 (5.61)	227.16 (12.45)	196.72 (19.34)	-13.34 (6.76)
Stroop Congruent ACC (%)	73.40 (7.77)	67.23 (8.37)	15.55 (10.31)	64.16 (7.37)	49.55 (6.40)	19.85 (8.70)
Stroop Incongruent ACC (%)	55.93 (8.58)	59.57 (7.54)	-12.55 (10.02)	53.32 (9.57)	38.58 (9.32)	26.70 (21.80)
Stroop Congruent Correct RT (ms)	1036.96 (64.92)	1076.96 (44.77)	11.71 (6.67)	1177.77 (59.67)	1093.75 (86.21)	-6.36 (6.35)
Stroop Incongruent Correct RT (ms)	1223.20 (64.45)	1166.91 (51.29)	-10.64 (3.15)	1255.31 (60.45)	1179.39 (112.52)	-4.22 (10.42)

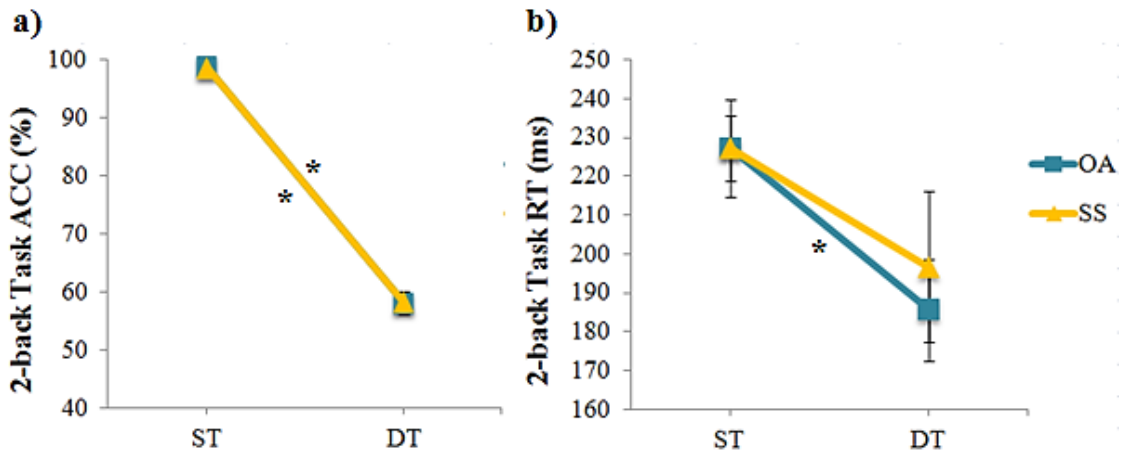

Figure 6.2. *Differences between single-task (ST) and dual-task (DT) for; a) 2-back percentage accuracy (ACC: +/- SEM) and; b) 2-back task reaction time (RT) in ms (+/- SEM), in both the older adult (OA) and stroke survivor (SS) groups (* indicates significance at the Bonferroni adjusted alpha).*

6.3.3.1 Cognitive DTC

See Table 6.4 for all mean and *SEM* DTC values. Separate comparisons of RT DTC values and ACC DTC values were made across tasks and between the groups. There were no differences between the two groups on accuracy DTC values (all $t < .316$, all $p > .108$) or RT DTC values (all $t < 1.96$, all $p > .064$). Comparing across tasks, there was a greater change (DTC) in accuracy on the 2-back DT ($M = 40.42$, $SEM = 2.17$), than on incongruent Stroop DT trials ($M = -12.55$, $SEM = 10.02$) in the OA group [$t(10) = 5.10$, $p < .001$]. This finding is due to the decline in accuracy on the 2-back in the DT condition, but a small increase in accuracy on incongruent trials in the Stroop DT. There was a significant difference in RT DTC between the 2-back ($M = -20.43$ $SEM = 5.61$) and congruent Stroop trials ($M = 11.71$, $SEM = 6.67$) in the OA group: $t(10) = -3.69$, $p = .004$. This is due to the faster RTs on the DT in the 2-back (DT improvement) compared to the slower RTs (DT cost) on the congruent Stroop DT in the OA group. Within the SS group, there was a significant difference between the Motor task RT DTC

and both the 2-back [$t(9) = 4.13$, $p = .003$] and congruent Stroop [$t(10) = 3.61$, $p = .005$] RT DTC. There was a significant difference between the increased RTs (dual-task cost) on the Motor DT ($M = 15.91$, $SEM = 7.53$) and the decreased RTs on the 2-back ($M = -13.34$, $SEM = 6.76$) and congruent Stroop DT ($M = -6.36$, $SEM = 6.35$). See Figure 6.3 for DTC (relative change) in: a) mean accuracy and: b) mean reaction time performances.

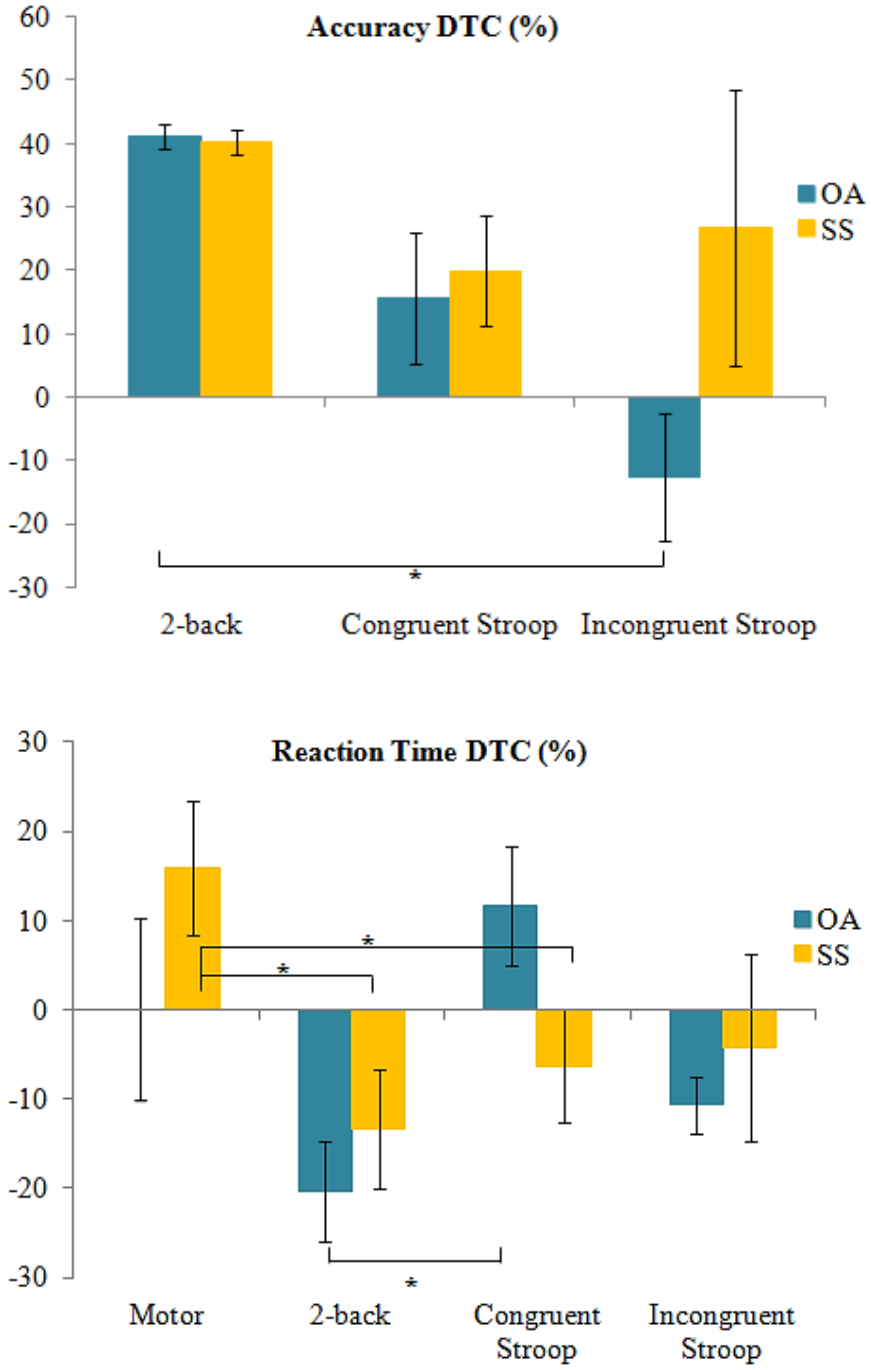

Figure 6.3. *Mean percentage dual-task change (DTC) in; a) accuracy (+/- SEM); and b) reaction time (+/- SEM), for each relevant dual-task in both the older adult (OA) and stroke survivor (SS) groups (* indicates significance at the Bonferroni adjusted alpha).*

6.3.4 Electrophysiological data

Concurrent EEG recordings were carried out during the seated ST cognitive tasks. Stimulus-locked ERPs were identified from the grand averages for each task and compared between the groups and across task conditions (where relevant). See Table 6.5 for all ERP component mean and *SEM* values. For the Motor task, we identified a positive component prominent at electrode site O2, maximal between 200-310ms, that peaked at 240ms (P2), and a later negative component at Oz between 330-580ms, peaking at 450ms (N450). There were no significant differences between the OA and SS groups on either component [P2: $t(22) = 3.61$, $p = .005$; N45: $t(10) = 3.61$, $p = .005$].

For the 2-back task, three ERP components were identified: a P2 component at P7 and T8 maximal between 200-380ms, an N4 component at Oz between 320-500ms, and a late positive component peaking at 670ms and 630ms at O2 for the OA and SS groups, respectively (P6 window: 500-800ms). There was no main effect for group or electrode site on the P2 component amplitude [group: $F(1, 21) = 1.47$, $p = .239$, $\eta^2 p = .065$; site: $F(1, 21) = 0.19$, $p = .672$, $\eta^2 p = .009$]. There were also no difference between the OA and SS group on the N4 component amplitude [$t(22) = -1.13$, $p = .270$], or later P6 component amplitude [$t(22) = 0.08$, $p = .936$].

On the Stroop task, we identified a P2, N3, Late Positive Component (LPC) and a broad Late Posterior Negativity (LPN). However, it is of note that the LPC and LPN had smaller, less distinct ERP morphologies, as can be seen in Figure 6.4. The P2 peak was maximal between 200-340ms at channels O2, T8 and T7. A 2 x 2 x 3 mixed factorial ANOVA revealed no main effects for group [$F(1, 20) = 0.55$, $p = .467$, $\eta^2 p = .027$], condition (congruent or incongruent) [$F(1, 20) = 0.08$, $p = .777$, $\eta^2 p = .005$], or electrode channel site (O2, T8 or T7) [$F(2, 40) = 0.20$, $p = .817$, $\eta^2 p = .010$].

Table 6.5. *Mean (and standard error of the mean) amplitude values for cognitive-associated event-related potential components, on each task condition, in both the older adults (OA) and stroke survivor (SS) group.*

Task	ERP Component	Channel	**OA**	**SS**
Motor task	P2	O2	2.37 (0.65)	2.50 (0.39)
	N450	Oz	-1.84 (0.38)	-1.64 (0.39)
2-back task	P2	P7	0.32 (0.22)	0.71 (0.18)
		T8	0.32 (0.14)	0.69 (0.20)
	N4	Oz	-0.81 (0.27)	-0.34 (0.33)
	P6	O2	1.40 (0.22)	1.36 (0.37)
Congruent Stroop task	P2	O2	0.61 (0.44)	1.06 (0.31)
		T8	0.82 (0.40)	1.18 (0.26)
		T7	-0.19 (0.48)	1.19 (0.28)
	N3	O2	-1.37 (0.45)	-0.79 (0.46)
	LPC	PO3	-0.62 (0.51)	-0.92 (0.88)
	LPN	PO4	1.38 (0.36)	1.32 (0.35)
Incongruent Stroop task	P2	O2	1.41 (0.73)	0.23 (0.38)
		T8	1.21 (0.65)	0.83 (0.47)
		T7	0.49 (0.38)	1.36 (0.37)
	N3	O2	1.64 (0.28)	0.83 (0.62)
	LPC	PO3	-1.25 (0.45)	-1.22 (0.28)
	LPN	PO4	-0.80 (0.28)	-1.44 (0.39)

The N3 peak was prominent at channel O2 and maximal between 290-430ms. A 2 x 2 mixed between-within ANOVA for peak amplitude showed no main effect for group [$F(1, 21) = 0.11$, $p = .748$, $\eta^2p = .005$], but did reveal a main effect of condition [$F(1, 21) = 30.15$, $p < .001$, $\eta^2p = .589$]. Follow-up comparisons showed greater mean amplitude for the congruent condition ($M = -1.37$, $SEM = 0.45$) in the OA group (but not the SS group), compared to the incongruent trials ($M = 1.73$, $SEM = 0.29$): $p < .001$. The late positive component (LPC) between 420-850ms was maximal over channel PO3. A 2 x 2 mixed factorial ANOVA on peak amplitude revealed no main effect for group [$F(1, 22) = 0.07$, $p = .793$, $\eta^2p = .003$], nor condition [$F(1, 22) = 0.60$, $p = .447$, $\eta^2p = .027$]. There were also no significant main effect for group on the late negativity maximal between 900-1300ms at channel PO4 [group: $F(1, 22) = 1.28$, $p = .270$, $\eta^2p = .055$]. However, there was a main effect for condition [$F(1, 22) = 41.64$, $p < .001$, $\eta^2p = .654$]; whereby both groups had a greater amplitude in the congruent condition (OA: $M = 1.38$, $SEM = 0.36$; SS: $M = 1.32$, $SEM = 0.35$) than the incongruent condition (OA: $M = -0.80$, $SEM = 0.28$; SS: $M = -1.44$, $SEM = 0.29$): all $p = .001$.

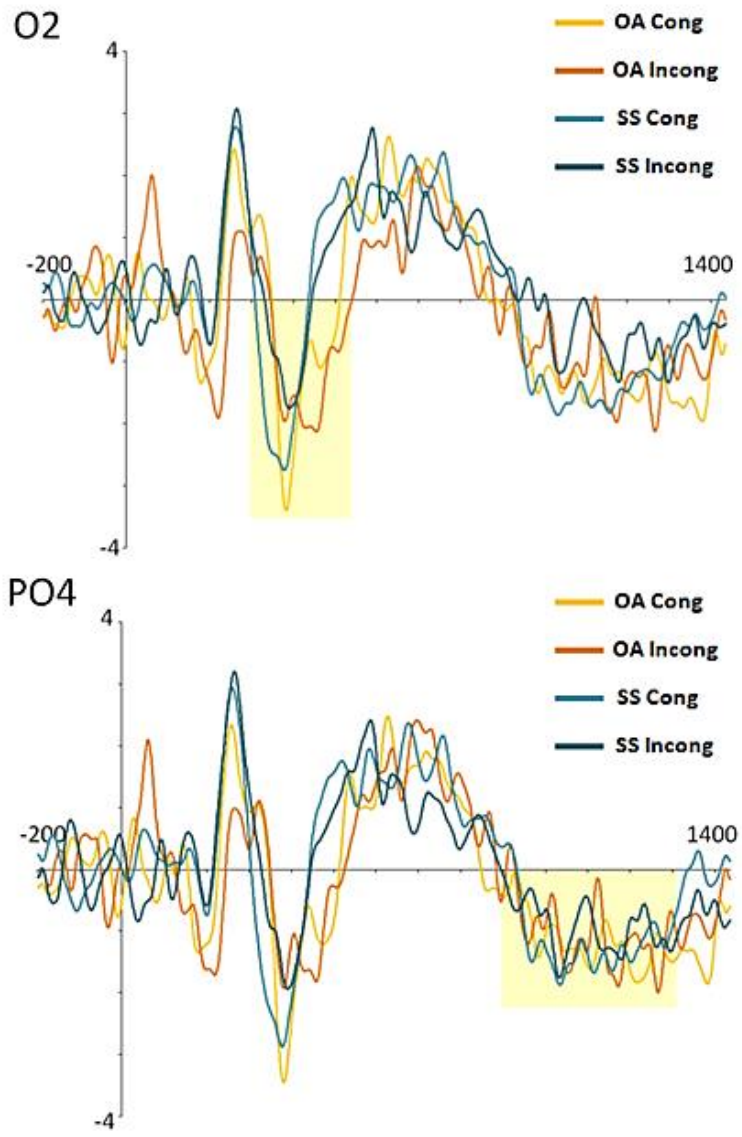

Figure 6.4. *Stroop task N3 at O2 and late posterior negativity at PO4 measured in microvolts (mV: y-axis) over time (ms: x-axis), for the older adults on congruent trials (yellow) and incongruent trials (orange), and the stroke survivors on the congruent (blue) and incongruent (dark blue) trials. On average, 1.22% of trials were rejected for the CC condition, and 2.56% were rejected for the IC condition.*

6.4 Discussion

We predicted that stroke survivors would have slower gait speeds in ST and DT conditions in comparison to the age-matched control group. While the stroke survivor sample was slower overall, there were no significant differences between the groups on any gait measures. This was surprising, as previous work had documented impaired gait post-stroke in comparison to controls. Most commonly, reduced gait speed has been identified as characteristics of post-stroke gait (Beyaert et al., 2015; Huitema et al., 2004; Olney & Richards, 1996; Weerdesteyn et al., 2008). However, other impaired gait characteristics such as decreased stride length and cadence post-stroke have been evidenced to recover over a longer period of time post-rehabilitation (Jonsdottir et al., 2009; Olney & Richards, 1996; Patterson et al., 2008), which may have been the case here. Interestingly, our stroke survivor sample had a faster baseline mean gait speed than previously reported speeds for even high-functioning survivors (Beyaert et al., 2015; Huitema et al., 2004; Olney & Richards, 1996). Additionally, our older adult group also had a slower mean gait speed than national reference data reported by Kenny et al. (2013). Therefore, it is possible that we recruited a slightly poorer performing control group and particularly well-recovered stroke survivor group, which could account for the lack of differences between these two groups on gait measures at baseline, and the equivalence between the groups on the control measures.

We also hypothesised that the stroke survivors would show greater detrimental changes (costs) in speed with the executive 2-back and Stroop dual-tasks. However, we found no significant changes in gait from ST to DT conditions for any of the three tasks. In terms of DTC in performance (relative change), we did not find clear patterns suggesting differences between the executive and non-executive domain tasks. We did

see cognitive costs (lower accuracy) on the 2-back working memory task for both groups. Interestingly, on incongruent trials of the Stroop we also saw increased accuracy in controls, and longer RTs in the stroke survivors. This was surprising as most participants indicated to the experimenter that the Stroop task was the most difficult, and it took the longest amount of time to explain the rules and instructions in most cases. Looking at accuracy scores, they are close to 50% on both the ST and DT conditions in the stroke survivor group (and to a lesser extent in the control group). This may indicate that stroke survivors responded at chance when unsure of the correct response (which could also explain how participants were able to prioritise walking performance).

Overall, these findings are in contrast to previous work that has shown cognitive-motor interference on speed, stride time, and cognitive performance (D Hyndman et al., 2006; Patel & Bhatt, 2014; Plummer-D'Amato et al., 2008). In particular, Patel and Bhatt (2014) found that a Serial Subtraction task elicited greater costs on both cognitive and motor performance in the stroke survivors (with the Stroop task causing greater costs in the young adult group). However, we must note that the stroke survivor samples differed in this study and Patel and Bhatt's, in their time post stroke (230-438 vs. 2-60 days post-stroke, respectively). Also, some have argued that articulatory responding (like that on a Serial Subtraction task) could increase cognitive-motor interference on gait due to the increased respiratory load competing with motor processes during walking and talking (Dault, Yardley & Frank, 2003; Yardley, Gardner, Leadbetter & Lavie, 1999; D Hyndman et al., 2006b). Therefore, in comparison to Patel and Bhatt's study, it is possible that the cognitive tasks employed here caused less interference because they did not require articulatory responses.

In this study, it appears that while the stroke sample had slightly slower speeds, both groups were able to maintain gait performance throughout. This indicates that

participants did not find the dual-task condition too challenging. Perhaps the straight walkway or the tasks themselves were not challenging enough in this study. One study of obstacle crossing by Smulders et al. (2012) found that neither stroke nor control adults were impaired in motor performance while concurrently completing a Stroop task, yet the stroke group exhibited cognitive performance interference. Interestingly, the older adult controls did not show any dual-task interference effects, in either direction. This may help explain why we found no clear patterns of dual-task costs in our older adult group in the current study.

We also hypothesised that the stroke survivor group would exhibit subtle single-task cognitive impairments indicating impaired executive function; such cognitive effects were not observed here. Previously, Duffin et al. (2012) revealed subtle cognitive impairments post-stroke that are not identifiable with clinical MMSE® and MoCA measures of global cognition. However, these deficits were on tasks of spatial attention and processing (and associative memory), while the tasks used here targeted executive functions previously associated with gait control and fall risk (Dubost et al., 2006; Holtzer et al., 2007), and shown to be impaired post-stroke (Cumming et al., 2013). Similarly, we did not see any differences between the groups on stimulus-locked event-related potentials, only differences between the congruent and incongruent conditions of the Stroop (where amplitude was greater on the late negativity for congruent Stroop condition). Interestingly, the control older adults had a late negative potential on incongruent Stroop trials that was absent in SS group. As noted above, the SS group did appear to perform at chance accuracy, which may suggest participants did not fully engage in decision making that would require inhibitory processing on incongruent trials. This may account for the differences between the groups on these trials. However, as this EEG data appears quite noisy, and these differences did not match behavioural

performances, or correlate with gait differences between the groups, we are hesitant to interpret this difference between the groups in the context of gait performance.

One overarching explanation for the collective results here could be that our stroke survivor sample was not impaired, and was in fact well-recovered, consisting of relatively healthy older adults, akin to the control group. Sampling was limited by who was willing to volunteer from those contacted via Tallaght Hospital's patients records, and it may be the case that the inclusion and exclusion criteria employed thereafter ensured we only recruited people who had experienced a relatively mild stroke, or who had particularly good recovery. None had evidenced cognitive decline at time of discharge, and the exclusion criteria ensured they had good motor functioning (ability to walk at least 10m unaided and no other pre-existing musculoskeletal problems), perhaps identifying a particular subgroup of stroke survivors who had a successful recovery and return to function (some had returned to driving and work after rehabilitation).

Only two stroke survivors had experienced a fall post-stroke event (comparable to our control group). Thus, we could not subdivide the groups into fallers and non-fallers (particularly with this small sample size). Perhaps there are differences in cognitive capacity and gait control between stroke survivors who fall and those who do not, with non-fallers exhibiting better cognitive and motor (and dual-task) performance recoveries, returning to functioning close to that of age-matched controls. Further research should attempt to replicate these findings and focus on comparing fallers and non-fallers post-stroke, with monitoring of both motor and cognitive (and dual-task) recovery and reacquisition over time post-stroke. It may be the case that we can evidence the cognitive-motor link in simultaneous recovery (as well as impairment) in both.

6.4.1 Conclusion

This study is different to previous literature in that it compares different executive tasks to a non-executive control dual-task, and investigated subtle cognitive and electrophysiological impairments post-stroke, which may be related to gait impairments and fall-risk. Overall, the data did not support our hypotheses, and we were unable to identify any clear markers (dual-task, cognitive or electrophysiological) of gait impairments post-stroke. Further research should continue to compare the effects of different dual-tasks on gait control post-stroke, and consider neuroimaging techniques to aid understanding of neurocognitive and motor recovery, which may explain dual-task capabilities after a stroke event. In particular, more studies should investigate differences between those who do and do not fall post-stroke, and aim for a time window closer to the stroke event.

Chapter 7

General Discussion

The overall objective of this research was to investigate the interaction between motor and cognitive factors contributing to gait instability and falls in older adults and stroke survivors. This thesis explored the cognitive control of gait and dual-task ability, and the related underlying neural activity, with a goal to identify any higher-level neurocognitive marker of fall-risk that could be of use in future work to develop alternative screening and intervention measures. The key aims of this thesis were: to compare cognitive performances across the sample groups and relate cognitive scores to specific walking gait characteristics: to identify the specific cognitive functions impaired in older fallers and stroke survivors and the associated neural processes underlying these impairments, and: to determine if PC-based neuropsychological tasks could identify fallers from non-fallers across these samples.

We hypothesised that there would be differences between different specific executive and non-executive tasks, revealing a greater role of executive function processes in the control of dual-task gait and fall-risk. We also predicted that poorer executive single- and dual-task performances would be associated with gait impairments and fall-risk, and that these behavioural performance differences would be reflected in the associated electrophysiological ERPs.

7.1 Overview of Findings

In Chapter 3 we found that executive function (EF) tasks of visuospatial attention, working memory and information updating elicited more compensatory changes in gait performance (slower speed and stride time, but maintained variability) than the control motor response task. For all EF tasks, it appears that gait performance was adapted in order to maintain cognitive performance, except on the 2-back task. The 2-back task revealed additional changes in cognitive performances as well as gait, indicating that

working memory resources play a greater role in dual-task walking than the other EF processes. These findings highlighted the relative role of higher-level attention and executive function in the control of dual-task gait in healthy young adults that goes beyond simple diversion of attention or motor response task load. Additionally, we concluded that a longer 15m walkway distance (rather than 5m) was better suited to allow for more steady state walking gait cycles during single- and dual-tasks.

In Chapter 4, we tested healthy young and older adults from the community and found that the same EF tasks elicited greater changes in gait speed and stride time parameters during DT walking, than comparative non-executive verbal and motor response tasks. These effects were more prominent in the older adult group. Specifically, there appeared to be more overlap in shared resources for the tasks that taxed visuospatial attention and working memory/information updating, again indicating their role in the top-down control of dual-task gait. However, the changes in gait did not imply instability, but rather compensation to maintain stability while necessary EF resources are taxed. Furthermore, it appears again that participants prioritised cognitive performances, as there were no changes from ST to DT conditions.

In Chapter 5 we investigated the EF and electrophysiological correlates of gait in older fallers and non-fallers, compared to young controls. We found no differences in ST gait between any of the groups, and only found general age-related differences in neural and EF measures (lower accuracy and slower responses, as expected). This is in contrast to previous work associating gait speed and EF performances with falls (see Kearney, Harwood, Gladman, Lincoln, & Masud, 2013, for example). The only difference we found between the groups was in a P3-like ERP component that was present in the non-fallers on the Stroop task, but notably absent for the faller group and young controls. The presence of this component, which we labelled P3a, in our non-falling group may reflect

the adaptive and plastic neural compensation associated with successful ageing in healthy older adults (in accordance with the scaffolding theory of ageing: Park & Reuter-Lorenz, 2009).

Finally, in Chapter 6 we examined the relationship between gait and executive function (EF), working memory and inhibition in stroke survivors. While the stroke survivors walked slower overall, we found no significant differences on ST or DT gait performances between or within the groups. Surprisingly, we also did not find significant differences between older adult controls and stroke survivors on executive cognitive measures, or the associated ERPs, but both groups had lower 2-back accuracy in the dual-task condition. Although we did not clearly identify a specific neurocognitive biomarker of fall-risk in older adults and stroke survivors, taken together, these findings indicate that EF cognitive function declines with age (evidenced in Chapter 4 and 5), and that executive working memory and visuospatial attention processes play a specific role in gait control in both young and (to a greater extent) older adults.

7.2 Cognitive-Motor Link

Recent literature suggests that executive processes in particular are related to falls and gait impairments in older adults and other cognitively-impaired clinical samples (Killane et al., 2014; Morris, Lord, Bunce, Burn, & Rochester, 2016; Muir et al., 2013), and play a role in controlling gait during dual-task walking (Al-Yahya et al., 2011; Chu, Tang, Peng, & Chen, 2013; Gomes et al., 2016). Our dual-task results support this literature by revealing a consistent trend of effects for EF tasks affecting pace and rhythm (associated with EF and global cognition, respectively) measures more than the non-EF tasks, and more so in the older adults. It is of note that these changes in gait appear more compensatory than indicators of instability and fall-risk (in the absence of changes in

variability). One strength of the findings presented here is that these EF tasks reveal *comparatively* greater DT costs for EF tasks than other non-executive–but still attention-demanding–control tasks (augmenting most previous studies). Comparing different EF and non-EF tasks may ameliorate the current problem of methodological heterogeneity in the literature regarding the choice of secondary task (Al-Yahya et al., 2011). Further work should make planned comparisons across and within specific cognitive domains, with varying task complexity, in order to continue to clarify the selective higher-level processes involved in gait control.

Interestingly, it was clear that EF tasks can also elicit some DT costs in healthy young adults, which indicates that there are top-down executive inputs for even healthy "normal" gait. This negates the argument that healthy gait is "automatic" or solely controlled by bottom up and lower-level cortical inputs. However, the exacerbated DT costs in older adults may be attributable to age-related decline in EF functions, or to an increased reliance on EF top-down control of gait in the face of sensorimotor decline (or both). This may be further supported by the potentially compensatory P3-like sustained attention/inhibitory associated component exhibited in the older non-fallers (those ageing successfully), that was noticeably absent in older fallers. Together, these findings are consistent with the resource capacity theories of attention and multitasking, and the older adult results corroborate the CRUNCH, STAC and somewhat with the PASA models of neurocognitive ageing (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008; Park & Reuter-Lorenz, 2009a; Reuter-Lorenz & Cappell, 2008). In light of this, we propose that working memory and sustained attention EF tasks may be the most sensitive for identifying older adults with who are using increased compensatory top-down control of gait, which may be a tentative marker of less successful ageing generally, and of further healthcare problems in the future.

We did observe age-related declines on single-task cognitive performances across studies, with some reflecting age-related differences in the associated ERPs. However, more critically, we did not see poorer EF performances in older fallers compared to non-fallers, or young adults. This was a surprising finding that contradicts much of the previous literature, but that may be explained by some limitations of our sampling method (discussed below). Another unexpected finding was that we did not observe any differences between any of the young, older faller or non-faller groups on single-task baseline "normal" walking gait. We must consider that the measures utilised here were perhaps not sensitive enough to identify subtle impairments in otherwise healthy and relatively young older adults and idiopathic fallers. Regarding the baseline gait performances, we have highlighted in previous chapters that the ST straight, level walkway assessment in the laboratory, devoid of obstacles, and with few environmental distractions, may not be a sensitive measure of subtle gait impairments in idiopathic fallers. In particular, the association between falls and EF performances in cross-sectional and longitudinal research may be difficult to discern with a simple-walk gait assessment in the laboratory, given that falls during walking in the "real world" most likely occurred in a far more challenging environment and terrain, with distractions and sudden perturbations, and most likely all while multitasking.

The last finding that was quite surprising was that it appears the stroke survivors recruited here at 1+ years post-stroke event had recovered cognitive and motor capacities to those equivalent in undiagnosed age-matched controls. Although this contrasts with some previous studies evidencing subtle cognitive impairments and DT costs post-stroke, most of the limited work thus far has tested patients at an earlier stage of recovery, or with different tasks (Duffin et al., 2012; Wang et al., 2015). This apparent recovery in our stroke survivor sample was a surprising, but affirming finding, highlighting the plastic

adaptability of the neural mechanisms underlying gait and cognitive control. However, in light of the other results evidencing a role of top-down control in even healthy young gait control, it may be that case that cognitive and motor control are intertwined, and not separable systems. Therefore, the period of motor recovery before "plateau" at 6 months post-stroke may have been a critical time for higher-level cognitive recovery also.

7.3 Consideration of Limitations

The key limitation of the findings presented here is the convenience sampling method for recruiting volunteer participants. Selection bias is a common challenge for most studies of ageing, whereby individuals who are "too healthy" (and thus still leading quite active and busy lives), and those who are "too ill" or experiencing functional or social barriers to participation can often not be engaged with, or decide to decline enrolment (Harada, Love, & Triebel, 2013). In this body of work, it appears that our older adult volunteers were relatively young and in a particularly good bill of health after meeting the inclusion and exclusion criteria. Furthermore, our stroke survivor group also appears to be comprised of individuals suffering less debilitating stroke attacks and/or those who experienced apparently successful subsequent rehabilitation and recovery of function. The lack of differences in gait characteristics between our groups limited our ability to address some of our aims, as we set out to determine if cognitive performances and the correlated ERPs were related to impaired gait and falls.

This self-selected enrolment of participants has implications for the characteristics of our sample and the generalisability of these findings to the wider population of older adults and stroke survivors. This is further impacted by our relatively small sample sizes in comparison to larger nationally-representative studies. These samples were limited by the number of "fallers" and patients who volunteered in particular, with only 8 volunteer

older fallers in Chapter 5. In Chapter 6, 11 stroke survivors that responded to the invitation letter also met the inclusion/exclusion criteria, and only two stroke survivors reported a history of falls. This restricted us from making faller and non-faller group distinctions for more specific investigation of the role of EF in gait stability and falls post-stroke. Furthermore, stroke is considered a highly heterogeneous syndrome, further hindering the interpretation and generalisability of stroke research results.

Concurrently, the baseline gait speeds reported for all studies here were comparatively slower than representative normative values or those reported by others in previous research (for example see Kenny et al., 2013). This may indicate that our samples are irregular, and not representative of the norm, presenting a further limitation for generalising our findings. For example, this could imply that we recruited older adults who perform slightly below the norm, and a group of particularly well-recovered stroke survivors, which would explain their equivalent performances on control tasks and on baseline gait and cognitive assessments. However, the fact that our younger adult groups also all exhibited slower gait speeds at baseline than previously reported brings our attention to the additional heterogeneity in the methodologies used for gait assessment within this field. With the recent advancement of new quantitative technologies for the assessment of gait, there are numerous protocols for gait assessment varying in length of walkway (as highlighted in Chapter 3), technology used (force plate, camera system, wearable sensors and the placement position) and type of data processing algorithm applied. For instance, the nationally-representative normative values provided by Kenny et al. (2013) were calculated from 2 walks measured on a pressure sensor matt, whereas we recorded kinematic data with wearable sensors over longer distances and recording times. Furthermore, the values provided by Kenny et al. were compared only to speeds

previously recorded on the same equipment, and were found to be the same or slightly faster than those reported prior (which may also explain our slower baseline speeds here).

7.4 Future Directions

To address some of the limitations of the current work, and those of the field itself, a longitudinal study of the cognitive-motor link, via dual-tasking, would be valuable for understanding the effects of ageing on top-down control of gait. Longitudinally, we could compare multiple dual-tasks that target distinct and specific higher-level executive and non-executive processes, to specifically investigate the impact of age-related neural and cognitive changes on gait control and fall-occurrence in both healthy older adults and those with cognitive impairment. Similarly, collecting longitudinal data from stroke survivors throughout the recovery process would contribute immensely to understanding the recovery and/or re-automaticity of gait control. Furthermore, in order to understand the interdependence between cognition and gait following stroke, a longitudinal study examining specific motor, cognitive and neural recovery from time of stroke to recovery plateau, and beyond, could aid our understanding of the cognitive-motor link. Here, neuroimaging and electrophysiological measures are vital, and we urge for the continued use of such measures to aid in understanding the neural mechanisms recruited for gait control. The recent development of mobile EEG recording protocols while walking may be one avenue through which to explore this cognitive-motor link (De Sanctis, Butler, Green, Snyder, & Foxe, 2012). Furthermore, the use of neuroimaging and physiological recording techniques will not only aid in clarifying the neural mechanisms of cognitive and motor control, but could also translate to the clinical setting for neural screening of fall risk in older adults and clinical samples.

Furthermore, we stress that it is as important to understand normal healthy young and ageing gait control, and successful recovery of cognition and gait post-stroke, as it is to understand the control systems when they fail to function or recover. As evidenced here, young adults reveal top-down EF processes are needed for dual-task gait, and we also must acknowledge the heterogeneity in neurocognitive decline with ageing, and the heterogeneous nature of stroke. Longitudinal studies with larger samples could identify neural or cognitive markers of successful and non-successful ageing or recovery that would have a substantial beneficial impact on developing clinical screening and rehabilitation protocols.

7.5 Wider Implications and Applications

Clinical falls training techniques often ignore spatial cognitive aspects, and the current clinical assessment model employed in Ireland (the Mini-Mental State Examination; MMSE, Folstein, Folstein, & McHugh, 1975) has been criticised as being insufficient in assessing cognitive deficits and for diagnosis alone (Strauss, Sherman, & Spreen, 2006). The MMSE model of patient care also only offers a single standardised rehabilitation package designed to "fit-all", and is compromised by its inability to identify and remediate subtle cognitive deficits. The most direct application of the work presented here and elsewhere is for developing an executive function cognitive training intervention that may improve top-down control of gait in those with gait impairments and a history of falls. While some dual-task training interventions have been developed recently, the problem of methodological variability and an overreliance on targeting global cognitive function has yielded mixed findings regarding the efficacy of these protocols (Menant, Schoene, Sarofim, & Lord, 2014; Plummer-D'Amato et al., 2008).

However, recent reviews from other areas show that EF training works (particularly in children), with computerised training of working memory in adults showing promise (Diamond & Lee, 2011; Morrison & Chein, 2011; Shipstead, Lindsey, Marshall, & Engle, 2014). Currently, the medical model focuses primarily on the anatomical functioning of the body and lower limbs for treatment of falls, which has not been evidenced to reduce future falls in older adults (Cadore, Rodríguez-Mañas, Sinclair, & Izquierdo, 2013; Teasell, McRae, Foley, & Bhardwaj, 2002). Incorporating specific EF elements into exercise or physiotherapy rehabilitation protocols, or developing and integrating an easy-to-use computer-based training tool into the medical rehabilitation package (and for continued use at home), could improve an individual's gait stability (alleviating some of the negative psychosocial consequences of falls). Furthermore, for individuals who are bed- or chair-bound soon after a stroke attack (or others with a motor impairment and known high fall-risk), an alternative computer-based intervention may facilitate earlier recovery of the neural pathways underlying higher-level cognitive control and their compensatory links to the motor cortex, from the safety of a chair or bed, without risk of falling. Given the importance of executive functions for carrying out many everyday tasks, such interventions would surely have wide reaching benefits for other aspects of recovery that go beyond gait control.

With the continued development of more sophisticated neuroscientific brain stimulation techniques such as tDCS and Transcranial Magnetic Stimulation (TMS), there is also a possibility to stimulate EF-associated frontal areas of the cortex to improve balance and gait control in those with impairment (building on the tDCS work by Manor et al., 2016, evidencing reduced DT costs in older adults 20 minutues after stimulation to the left PFC). Alternatively, identifying the neurobiological link between motor and cognitive control in ageing may lead to the development of neuropharmacological

interventions that could enhance cognitive EF function by improving the neuromodulation of monoamines such as dopamine (Arnsten & Li, 2005; Li, Lindenberger, & Sikström, 2001).

These implications also extend beyond older adult fallers and stroke survivors, and to the wide range of cognitively impaired population such as those with MCI, dementia and frontal brain injuries/dysexecutive syndrome. Overall, the hope is that novel rehabilitation techniques that promote neurocognitive plasticity and compensation (via exercise, brain stimulation, cognitive enhancement) can be developed to supplement the current medical model of rehabilitation, improve gait stability, and prevent future falls in both diagnosed and undiagnosed older adults. This may help ameliorate the growing burden of falls on both national and international healthcare systems.

7.6 Conclusion

In conclusion, the current thesis reports four experiments investigating the role of specific executive functions tasks in the control of gait, and their relationship to fall-risk in healthy young and healthy older adults with and without a history of falls, and a supposed high-fall risk sample of stroke survivors. Results suggest that executive top-down processes play a role in gait control during dual-tasking, in both healthy young adults and older adults to a greater extent, that there may be adaptive neural compensation in older non-fallers aging successfully, and that there can be significant recovery of both cognitive and motor function after 6 months post-stroke. These findings offer support for the resource capacity and compensatory theories of neurocognitive ageing, which highlights the possibility of developing neurocognitive enhancement interventions for the prevention of falls.

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Appendices

Appendix A: Montreal Cognitive Assessment

Appendix B: National Adult Reading Test

Appendix C: National Adult Reading Test Scoring Manual

Appendix D: Falls Efficacy Scale-International

Appendix E: Fall History Questionnaire

Appendix F: Maynooth Ethical Approval (Chapter 3 and 4)

Appendix G: Maynooth Ethical Approval (Chapter 5)

Appendix H: Maynooth Ethical Approval (Chapter 6)

Appendix I: AMNCH Ethical Approval (Chapter 6)

Appendix J: Informed Consent (Chapter 3)

Appendix K: Informed Consent (Chapter 4)

Appendix L: Informed Consent (Chapter 5)

Appendix M: Older Adult Informed Consent (Chapter 6)

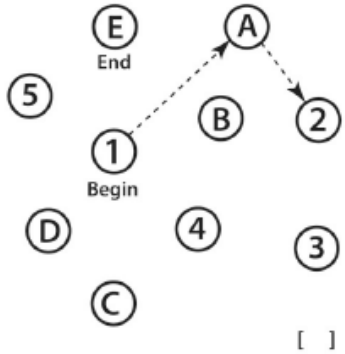
Appendix N: Patient Information Leaflet and Informed Consent (Chapter 6)

Appendix A

MONTREAL COGNITIVE ASSESSMENT (MOCA)
Version 7.1 Original Version

Education :
Sex :
Date of birth :
DATE :

VISUOSPATIAL / EXECUTIVE



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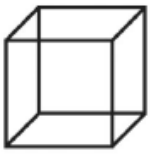


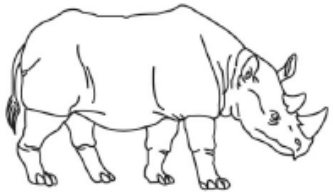
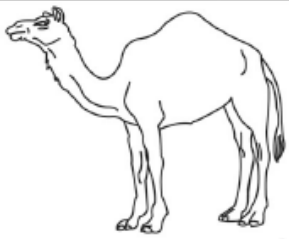
[ ] [ ]

Draw CLOCK (Ten past eleven)
(3 points)

[ ] Contour [ ] Numbers [ ] Hands

POINTS __/5

NAMING

[ ] [ ] [ ] __/3

MEMORY Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED
1st trial					
2nd trial					

No points

ATTENTION Read list of digits (1 digit/ sec.).

Subject has to repeat them in the forward order [ ] 2 1 8 5 4
Subject has to repeat them in the backward order [ ] 7 4 2 __/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors
[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B __/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65
4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt** __/3

LANGUAGE Repeat : I only know that John is the one to help today. [ ]
The cat always hid under the couch when dogs were in the room. [ ] __/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] _____ (N ≥ 11 words) __/1

ABSTRACTION Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler __/2

DELAYED RECALL

	Has to recall words WITH NO CUE	FACE [ ]	VELVET [ ]	CHURCH [ ]	DAISY [ ]	RED [ ]	Points for UNCUED recall only
Optional	Category cue						
	Multiple choice cue						

__/5

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City __/6

www.mocatest.org
Normal ≥ 26 / 30

TOTAL __/30
Add 1 point if ≤ 12 yr edu

Administered by: _____

Appendix B

National Adult Reading Test

Ache	Simile
Debt	Aeon
Psalm	Cellist
Depot	Zealot
Chord	Abstemious
Bouquet	Gouge
Deny	Placebo
Capon	Façade
Heir	Aver
Aisle	Leviathan
Subtle	Chagrin
Nausea	Détente
Equivocal	Gauche
Naïve	Drachm
Thyme	Idyll
Courteous	Beatify
Gaoled	Banal
Procreate	Sidereal
Quadruped	Puerperal
Catacomb	Topiary
Superfluous	Desmesne
Radix	Labile
Assignate	Phlegm
Gist	Syncope
Hiatus	Prelate

Appendix C

FOR EXPERIMENTER'S USE

NART pronunciation and definitions

Word	Say	Definition
Ache	*Rhymes with* take	Any dull, continuous pain
Debt	Det	Anything which one owes to another
Psalm	Sahm	A sacred song or hymn
Depot	Deppo (or deepo)	A place where things are kept or stored
Chord	Kord	1. *Maths*: a straight line segment joining two points on a curve. 2. a string on a musical instrument 3. *Music*: a group of three or more notes played together in harmony
Bouquet	Bo-kay or boo-kay	1. a bunch of flowers 2. the characteristic smell of wines or liqueurs
Deny	De-nigh	1. to declare as untrue 2. to refuse to believe or acknowledge 3. to refuse to grant
Capon	Kay-pon	A domestic cock which has been castrated to improve its flesh for eating
Heir	Air	1. a person who inherits, or will inherit, money, property, title, etc. 2. a person, group or society to which something such as tradition, ideas, etc. is passed on
Aisle	Ile	Any passage between blocks of seats, as in a theatre
Subtle	Sutt'l	Fine, slight or delicate, so as to be difficult to detect, etc.
Nausea	Nawsia	1. a feeling of sickness in the stomach, often followed by vomiting 2. a feeling of extreme disgust or loathing
Equivocal	Ikkwivvi-k'l	Ambiguous or unclear
Naïve	Nie-eev	Unaffected or unsophisticatedly simple and artless (free from deceit or cunning)
Thyme	Time	A low shrub with fragrant leaves used in cooking
Courteous	Kertius	Polite and well-mannered
Gaoled	Jaled	Also spelt **jail**: a building where convicted criminals are kept
Procreate	Pro-kree-ate	To produce offspring
Quadruped	Kwodroo-rep	Any animal with four feet
Catacomb	Katta-koom *or* Katta-kome	(*usually plural*) an underground cemetery consisting of tunnels with recesses for graves
Superfluous	Soo-perfloo-us	More than is needed
Radix	Ray-diks	Maths: a number used as the base of a system of numbers, logarithms, etc.
Assignate		

FOR EXPERIMENTER'S USE ONLY

Gist	Jist	The essential part of something
Hiatus	High-aytus	A gap or interruption
Simile	Simmi-lee	A figure of speech in which two unlike things are compared
Aeon	ee-on	An immensely long period of time
Cellist		
Zealot	zellot	1. an eager of enthusiastic person 2. a fanatic
Abstemious	Ab-steemius	Tending to eat and drink sparingly
Gouge	Gowj	1. *noun* a chisel with a curved blade for cutting blades 2. *verb* to scoop out with or as if with a gouge
Placebo	Pla-seebo	A medicine given to a patient for psychological reasons and having no physiological effect
Façade	Fa-sahd	1. the outside of a building 2. a false or deceptive exterior
Aver	a-ver	To declare in a positive way
Leviathan	Lev-eye-a-th'n	Anything which is very large, especially in the sea
Chagrin	Shagrin *or* sha-green	A feeling of vexation or disappointment
Détente	Day-tont	An easing or relaxing of strained relationships between countries
Gauche	goash	Awkward or tactless
Drachm	Dram	A unit of mass equal to about 3.89g
Idyll	Eye-dill *or* iddil	A short poem or piece of descriptive music concerned with romanticized rural life
Beatify	Bee-atti-fie	
Banal	Ba-nahl	Hackneyed, ordinary or trivial
Sidereal	Sigh-deeriul	Of or relative to the stars
Puerperal	Pew-er-peral	Of, relating to, or occurring during childbirth or the period immediately following
Topiary	To-pie-ary	Of, relating to, or being the practice or art of training, cutting, and trimming trees or shrubs into odd or ornamental shapes
Demesne	Da-mane *or* da-meen	1. the possession of land as one's own 2. the land and buildings possessed
Labile	Lay-bile	Changeable or unstable
Phlegm	Flem	Also called **sputum**: the thick mucus of the throat, brought up by coughing during a cold, etc.
Syncope	Sin-co-pay	1. the loss of consciousness resulting from insufficient blood flow to the brain 2. the loss of one or more sounds or letters in the interior of a word (as in fo'c'sle for forecastle)
Prelate	prellit	A high-ranking clergyman, such as a bishop or archbishop

Nart Errors	Predicted Full Scale IQ	Predicted Verbal IQ	Predicted Performance IQ
0	131	127	128
1	129	126	127
2	128	125	126
3	127	124	125
4	126	123	123
5	124	122	122
6	123	121	121
7	122	119	120
8	121	118	119
9	120	117	118
10	118	116	117
11	117	115	116
12	116	114	115
13	115	113	114
14	113	111	112
15	112	110	111
16	111	109	110
17	110	108	109
18	108	107	108
19	107	106	107
20	106	105	106
21	105	103	105
22	103	102	104
23	102	101	102
24	101	100	101
25	100	99	100
26	98	98	99
27	97	97	98
28	96	95	97
29	95	94	96
30	94	93	95
31	92	92	94
32	91	91	93
33	90	90	91
34	89	89	90
35	87	87	89
36	86	86	88
37	85	85	87
38	84	84	86
39	82	83	85
40	81	82	84
41	80	81	83
42	79	80	82
43	77	78	80
44	76	77	79
45	75	76	78
46	74	75	77
47	73	74	76
48	71	73	75
49	70	72	74
50	69	70	73

Appendix D–FES

TINNETTI'S FALLS EFFICACY SCALE-INTERNATIONAL

PARTICIPANT..... AGE..... DATE.....

For each of the following activities,
please tick the box which represents how concerned you are that you might fall if you did this activity.

Question	Circle best answer			
	Not at all concerned	*Somewhat concerned*	*Fairly concerned*	*Very concerned*
Cleaning the house (e.g. sweep, vacuum or dust)	1	2	3	4
Getting dressed or undressed?	1	2	3	4
Preparing simple meals	1	2	3	4
Taking a bath or shower	1	2	3	4
Going to the shop	1	2	3	4
Getting in and out of a chair	1	2	3	4
Going up or down stairs	1	2	3	4
Walking around in the neighbourhood	1	2	3	4
Reaching for something above your head or on the ground	1	2	3	4
Going to answer the telephone before it stops ringing	1	2	3	4

Walking on a slippery surface (e.g. wet or icy)	1	2	3	4
Visiting a friend or relative	1	2	3	4
Walking in a place with crowds	1	2	3	4
Walking on an uneven surface (e.g. rocky ground, poorly maintained pavement)	1	2	3	4
Walking up or down a slope	1	2	3	4
Going out to a social event (e.g. religious service, family gathering or club meeting)	1	2	3	4

Score	

Appendix E–FHQ

Fall History Questionnaire

Fall Definition: *A sudden, unintentional change in position resulting in landing at a lower level (floor, ground or on an object), other than as a consequence of health/medical issues (sudden paralysis, epileptic seizure, medications, other sicknesses) or overwhelming external force.*

[Feder et al. 2000]

Please mark the answer box appropriate to you

1. Have you fallen in the past 12 months?

   YES ☐ **NO** ☐ *(if "NO", answer "N/A" for all remaining questions)*

2. Have you fallen more than once in the past 12 months?

   YES, twice ☐ **YES, more than twice** ☐ **NO** ☐ **N/A** ☐

3. Did you suffer any injuries because of a fall in the past 12 months?

   YES, from one fall ☐ **YES, from more than one fall** ☐ **NO** ☐ **N/A** ☐

4. Did you contact a health professional/seek medical attention for a fall in the past 12 months?

   YES, for one fall ☐ **YES, for more than one fall** ☐ **NO** ☐ **N/A** ☐

5. **If you have fallen in the past 12 months**, please state the **main** reason you fell (if you fell multiple times, you may select more than one option):

Environment ☐ (pavement, flooring, obstacle etc.) **Distraction** ☐ (multitasking, visual/ auditory distraction) **I don't know** ☐ **Other** ☐ **N/A** ☐

If "Other", please state here: _____

_____

_____

Appendix F

NATIONAL UNIVERSITY OF IRELAND, MAYNOOTH
MAYNOOTH, CO. KILDARE, IRELAND

NUI MAYNOOTH
Ollscoil na hÉireann Má Nuad

Dr Carol Barrett
Secretary to NUI Maynooth Ethics Committee

20 October 2011

Richard Roche
Psychology
NUI, Maynooth

RE: Application for ethical approval for the following:
"An investigation of spatial processing and navigation in elderly and stroke patients, relating to assessment and rehabilitation."

Dear Richard,

The ethics committee has evaluated the above project, and we would like to inform you that ethical approval has been granted.

Kind regards,

Dr Carol Barrett
Secretary, NUI Maynooth Ethics Committee

CC Elizabeth Walshe

Appendix G

NATIONAL UNIVERSITY OF IRELAND, MAYNOOTH
MAYNOOTH, CO. KILDARE, IRELAND

NUI MAYNOOTH
Ollscoil na hÉireann Má Nuad

Dr Carol Barrett
Secretary to NUI Maynooth Ethics Committee

12 March 2013

Elizabeth Walshe
Department of Psychology
NUI Maynooth

Application for ethical approval for the following:
Application Reference Number: BSRESC-2013-004
Committee meeting date: 26 February 2013
Project title: "Cognitive Processing and Gait in Young and Older Adults"

Dear Elizabeth,

The ethics committee has granted ethical approval for you to carry out the project described in your application, reference number BSRESC-2013-004.

This ethical approval has been granted for a period of 1 year, and will expire on 12 March 2014.

Any deviations from the project details submitted to the ethics committee will require further evaluation.

Kind regards,

Dr Carol Barrett
Secretary, NUI Maynooth Ethics Committee

CC Dr Richard Roche, Department of Psychology
Dr Sean Commins, Department of Psychology

Application reference number: BSRESC-2013-004

Appendix H

NATIONAL UNIVERSITY OF IRELAND, MAYNOOTH
MAYNOOTH, CO. KILDARE, IRELAND

Dr Carol Barrett
Secretary to NUI Maynooth Ethics Committee

NUI MAYNOOTH
Ollscoil na hÉireann Má Nuad

10 March 2014

Elizabeth Walshe
Psychology
NUI Maynooth

RE: Application for Ethical Approval for a project entitled:
'Investigating the Cognitive and Electrophysiological Processes Underpinning Walking Gait and Fall-Risk Post-Stroke'

Dear Elizabeth,

The Ethics Committee evaluated the above project and we would like to inform you that ethical approval has been granted.

Kind Regards,

Dr Carol Barrett
Secretary, NUI Maynooth Ethics Committee

C.c Dr Richard Roche, Department of Psychology

Appendix I

SJH/AMNCH Research Ethics Committee
David Willow david.willow@amnch.ie
Secretariat Phone: (01) 414 2342

THE ADELAIDE & MEATH HOSPITAL, DUBLIN
INCORPORATING
THE NATIONAL CHILDREN'S HOSPITAL

TALLAGHT, DUBLIN 24, IRELAND
TELEPHONE +353 1 4142000

Ms. Elizabeth Walshe
Department of Psychology
NUI Maynooth
Co. Kildare

21st January 2014

RE: Investigating the cognitive and electrophysiological processes underpinning walking gait and fall risk post strock
REC Reference 2013/12/09 /
REC Reference 2014/01/List 2

(Please quote REC reference and EudraCT number on all correspondence)

Dear Ms. Walshe,

With thanks for responses to conditions required by the Research Ethics Committee for the above study. These are satisfactory.

Good luck with the Study.

Yours sincerely,

David Willow
Secretary
SJH/AMNCH Research Ethics Committee

Appendix J

An investigation of cognitive processes and gait profiles

Researchers:
Elizabeth Walshe
Dept of Psychology
Maynooth University
Co. Kildare,
Ireland

Ph 01 708 6311

Supervisors:
Drs. Richard Roche, Seán Commins
Dept of Psychology
Maynooth University
Co. Kildare,
Ireland.

Ph 01 708 6069 or 01 708 6182

Letter of Informed Consent for Participation in Research at the Department of Psychology, NUI Maynooth.

Your participation is requested in an experimental study examining the examining the role of different mental processes in walking gait and balance. During the experiment, you will be asked to do a number of different cognitive tasks–such as simple memory, subtraction and visualisation tasks. Other tasks will involve balance and walking gait, requiring you to walk along a walkway a number of times at your normal pace while sensors record you movements. Sometimes we will ask you to walk while doing some fo the other simple tasks. You will also have some questionnaires to fill out.

The expected time for your participation will be approx. 45 minutes.

The specific nature of the study will be explained as soon as you have completed your session. The results of each individual's participation will be strictly confidential and will be kept in a locked cabinet in the Psychology Department. The results of your participation will be documented by subject number only. No names or individual identifying information will be recorded. With the exception of the researcher(s) involved in running this study, nobody will be allowed to see or discuss any of the individual responses. Your responses will be combined with many others and reported in group form in a scientific paper, but your own data will be available to you at your discretion. You may withdraw from the study at any time or you may withdraw your data up until the work is published.

Performance on these tasks does not provide any diagnostically relevant information. In the unlikely event that you experience any distress, discomfort or other negative experience as a result of participating in this study, you should contact the Student Counseling Service (708 3554) or Student Health Service (708 3878; both on campus and located very close to the Psychology Department) or contact your own GP.

I have read the above and understand the nature of this study and agree to participate. I also understand that I have the **right to refuse to participate** and that **my right to withdraw from participation at any time during the study will be respected with no coercion or prejudice**.

_____ _____

Participant signature Date

This research project has been approved by the Departmental Ethics Committee.

If during your participation in this study you feel the information and guidelines that you were given have been neglected or disregarded in any way, or if you are unhappy about the process, please contact the Secretary of the National University of Ireland Maynooth Ethics Committee at research.ethics@nuim.ie or +353 (0)1 708 6019. Please be assured that your concerns will be dealt with in a sensitive manner.

Appendix K

An investigation of cognitive processes and gait profiles in healthy young and older adults

Researchers:
Elizabeth Walshe, Alice Donnelly,
Shaun Carter & Caoimhe Sheridan
Department of Psychology
National University of Ireland, Maynooth
Co. Kildare,
Ireland

Ph 01 708 6311

Supervisors:
Drs. Richard Roche & Seán Commins
Lecturers
Department of Psychology,
National University of Ireland, Maynooth,
Co. Kildare,
Ireland.

Ph 01 708 6069 or 01 708 6182

Letter of Informed Consent for Participation in Research at the Department of Psychology, NUI Maynooth.

Your participation is requested in an experimental study taking place in the Department of Psychology at NUI Maynooth examining the role of particular mental processes in gait and balance. During the experiment, you will be asked to do a number of different cognitive tasks – such as simple memory, subtraction and visualisation tasks. Other tasks will involve balance and walking gait, requiring you to walk along a 15m walkway a number of times at your normal pace. Sometimes we will ask you to walk while doing some fo the other simple tasks. You will also have some questionnaires to fill out, which will ask about any history of falls or balance problems, and how confident you are at certain balance-dependent tasks, and other such questions. For all of the balance/walking tasks, we will make sure you are in no danger of falling over, as we will be there to support you, and they will be like everyday walking tasks.

The total time for your participation will be a maximum of one hour.

The specific nature of the study will be explained as soon as you have completed your session. The results of each individual's participation will be strictly confidential and will be kept in a locked cabinet in the Psychology Department. The results of your participation will be documented by subject number only. No names or individual identifying information will be recorded. With the exception of the researcher(s) involved in running this study, nobody will be allowed to see or discuss any of the individual responses. Your responses will be combined with many others and reported in group form in a scientific paper, but your own data will be available to you at your discretion. You may withdraw from the study at any time or you may withdraw your data up until the work is published.

Performance on these tasks does not provide any diagnostically relevant information. In the unlikely event that you experience any distress, discomfort or other negative experience as a result of participating in this study, you should contact the Student Counseling Service (708 3554) or Student Health Service (708 3878; both on campus and located very close to the Psychology Department) or contact your own GP.

Finally, if you suffer from **any** of the following, you may not be eligible to take part:

- severe visual impairments;
- history of epilepsy;
- currently taking psychoactive medication or balance-impairing medication;
- other relevant medical conditions;
- acute mobility conditions (lower limb amputation/recent joint replacement);
- labyrinthectomy;
- any muscular or bone problems that cause balance impairments.

- -

I have read the above and understand the nature of this study and agree to participate. I also understand that I have the **right to refuse to participate** and that **my right to withdraw from participation at any time during the study will be respected with no coercion or prejudice**.

____________________________________ ___________________

Participant signature Date

This research project has been approved by the University Ethics Committee.

If during your participation in this study you feel the information and guidelines that you were given have been neglected or disregarded in any way, or if you are unhappy about the process, please contact the Secretary of the National University of Ireland Maynooth Ethics Committee at research.ethics@nuim.ie or +353 (0)1 708 6019. Please be assured that your concerns will be dealt with in a sensitive manner.

Appendix L

An investigation of cognitive processing and walking gait in healthy young and older adults.

Researcher:
Elizabeth Walshe,
Department of Psychology
National University of Ireland, Maynooth
Co. Kildare,
Ireland

Ph 01 708 6311

Supervisors:
Drs. Richard Roche & Seán Commins
Lecturers
Department of Psychology,
National University of Ireland, Maynooth,
Co. Kildare,
Ireland.

Ph 01 708 6069 or 01 708 6182

Letter of Informed Consent for Participation in Research at the Department of Psychology, NUI Maynooth.

Your participation is requested in an experimental study taking place in the Department of Psychology at NUI Maynooth examining the role of particular brain areas and how they play a role in balance and falling. During the experiment, you will be asked to do a number of different tasks. You will also have some paper-based questionnaires to fill out, which will ask about your balance, any history of falls, your memory, and such questions. You will be asked to walk on a walkway/pathway indoors (15m), at your normal pace for a few minutes while we record your walking style and speed. This walking task poses no danger, as it will be like everyday walking, and we will be there to support you.

Other tasks will be on computer, where you will have to look at things appearing on the screen and respond to questions using a key press. During these computer tasks, we will record electrical brain waves by placing a cap on your head which will allow us to record electrical signals as your brain engages in the tasks you are doing (using a small EEG system). This procedure is safe, painless and non-invasive; it does not involve radiation, x-rays, magnetic fields or any other dangerous elements, so you should consider it similar to having your heart-rate or blood-pressure measured. The procedure involves applying a conductive gel to your scalp to help us get a clear signal from the brain, so you will need to wash your hair afterwards – washing and drying facilities will be provided for you.

The total time for any participation session will be a maximum of two hours.

The specific nature of the study will be explained as soon as you have completed your session. The results of each individual's participation will be strictly confidential and will be kept in a locked cabinet in the Psychology Department. The results of your participation will be documented by subject number only. No names or individual identifying information will be recorded. With the exception of the researcher(s) involved in running this study, nobody will be allowed to see or discuss any of the individual responses. Your responses will be combined with many others and reported in group form in a scientific paper, but your own

data will be available to you at your discretion. You may withdraw from the study at any time or you may withdraw your data up until the work is published.

In the unlikely event that you experience any distress, discomfort or other negative experience as a result of participating in this study, you should contact the Student Counseling Service (708 3554) or Student Health Service (708 3878; both on campus and located very close to the Psychology Department) or contact your own GP.

Finally, if you suffer from **any** of the following, you may not be eligible to take part:

	Yes	No
• severe uncorrected visual impairments;	☐	☐
• history of psychological/neurological impairment;	☐	☐
• severe head trauma resulting in unconsciousness;	☐	☐
• history of epilepsy;	☐	☐
• currently taking psychoactive medication;	☐	☐
• other relevant medical conditions;	☐	☐
• high blood pressure/heart condition;	☐	☐
• history of drug or alcohol problems;	☐	☐
• claustrophobia	☐	☐
• any muscular or bone problems that cause balance impairments.	☐	☐

I have read the above and understand the nature of this study and agree to participate. I also understand that I have the **right to refuse to participate** and that **my right to withdraw from participation at any time during the study will be respected with no coercion or prejudice**.

_____ _____

Participant signature Date

This research project has been approved by the Departmental Ethics Committee.

If during your participation in this study you feel the information and guidelines that you were given have been neglected or disregarded in any way, or if you are unhappy about the process, please contact the Secretary of the National University of Ireland Maynooth Ethics Committee at research.ethics@nuim.ie or +353 (0)1 708 6019. Please be assured that your concerns will be dealt with in a sensitive manner.

Appendix M

NUI MAYNOOTH
Ollscoil na hÉireann Má Nuad

THE ADELAIDE & MEATH HOSPITAL, DUBLIN
INCORPORATING
THE NATIONAL CHILDREN'S HOSPITAL

SJH / AMNCH & NUIM RESEARCH ETHICS COMMITTEE
Participant Information Leaflet

Study title: Investigating the Cognitive and Electrophysiological Processes Underpinning Walking Gait and Fall-Risk Post-Stroke.

Principal investigator's name: **Dr Ronan Collins**
Principal investigator's title: Asst. Professor of stroke medicine

Lead Investigator's name: **Elizabeth Walshe**
Lead Investigator's title: PhD Research Candidate
Telephone number of lead investigator: **0857136153**

You are being invited to take part in a research study to be carried out at NUI Maynooth and the Adelaide and Meath incorporating the National Children's Hospital (AMNCH), Tallaght.

Before you decide whether or not you wish to take part, you should read the information provided below carefully. Take time to ask questions–don't feel rushed and don't feel under pressure to make a quick decision.

You should clearly understand the risks and benefits of taking part in this study so that you can make a decision that is right for you. This process is known as 'Informed Consent'. You don't have to take part in this study. You can change your mind about taking part in the study any time you like. Even if the study has started, you can still opt out. You don't have to give us a reason.

Introduction

This study is investigating why there is an increased risk for falling in some older adults and post-stroke, what processes in the brain are important for maintaining balance, and what tasks or measures we can use to predict those at risk and prevent future falls. This study is being carried out by lead investigator Elizabeth Walshe, as part of an academic PhD qualification at the National University of Ireland Maynooth. This research is supervised by Drs. Richard Roche and Seán Commins of NUI Maynooth, and Dr. Ronán Collins of Tallaght Hospital. This project is funded by a PhD scholarship from the Irish Research Council.

Procedures

Why am I being asked to take part?
You are a community-dwelling adult over the age of 55, living in the surrounding areas of

Maynooth or Tallaght, without a diagnosis of stroke. Your participation will allow for a comparison between community-dwelling older adults (whether or not you have experienced a fall recently) and those with a diagnosis of stroke or dysexecutive syndrome.

What will participation involve?
All testing will take place at a time that suits you, for an average of 2 hours, and you will be given multiple opportunities to take a short break. Testing will take place either in NUI Maynooth or Tallaght Hospital, depending on your preference, where you will meet with lead investigator Elizabeth Walshe. Your testing results will be anonymous, with only an average group result being used academically for publication of the study's findings.

You will be asked to walk normally on a straight pathway for a few minutes while we record your walking movements with two wearable sensors (in some cases a digital video recording may be taken). You will then be asked to complete general questionnaires that will ask you about any previous experience of falls or balance concerns, and pen and paper tasks requiring you to read a list of words, recall some words and numbers, and complete some simple drawings. Computer-based tasks of memory, attention and motor abilities will also be used which will present an auditory tone or visual image, word or number on screen and ask you to respond with a mouse click or key press. As you engage in these tasks, tasks, we will record electrical brain waves by placing a cap on your head which will allow us to record electrical signals from the scalp. This recording procedure (an EEG cap with connecting electrodes and signal-enhancing gel) is akin to measuring your heart-rate or blood-pressure, in that it is completely safe, pain-free and non-invasive.

Benefits

You may not receive any benefit. As this is a research study, we cannot state that you will benefit personally from taking part. However, your participation in this study contributes to our understanding of falls and walking gait impairments in older adults and adults post-stroke. The findings from this study hope to identify if tasks of mental processes could be of use in future fall-risk screening and intervention.

Risks

This research is designed to be safe, pain-free and non-invasive. None of the tasks have been designed to be deceptive or stress-inducing in any way, and do not pose any risk beyond everyday real-world activities. The measurement of brain activity will require you to wear an electrode cap with a special gel to be used on the scalp to enhance the signal. This may require your hair to be washed after the study (these facilities will be provided for you). The gel is designed to be sensitive, but will be tested beforehand to ensure no negative experience. This procedure does not involve radiation, x-rays, magnetic fields or any other dangerous elements. If you feel any discomfort at any point while taking part, please inform the researcher (Elizabeth Walshe) immediately and the process can be stopped.

Exclusion from participation

You may not be eligible for this study if any of the following are true:
- You have severe (uncorrected) visual or auditory impairments
- You have a history of psychological/neurological impairment

- You have had a severe head trauma resulting in unconsciousness;
- You have a history of epilepsy;
- You have dementia, or moderate to severe aphasia;
- You are currently taking psychoactive medication;
- You have other relevant medical conditions (e.g. vestibular/musculoskeletal/orthopedic);
- You have unstable/uncontrolled high blood pressure/heart condition;
- You have a history of drug or alcohol problems;
- You have lower limb amputation, recent joint replacement;
- You have had a labyrinthectomy

Confidentiality

Records
Your identity will remain confidential and your name will not be published. If you take part, you will be assigned a code number in place of your name for all experimental documents and recordings, to ensure anonymity. All information will be stored on secure hard-drives and in locked filing cabinets in the Department of Psychology at the National University of Ireland Maynooth, which may only be accessed by the lead researcher and supervisors (in accordance with the Data Protection Act of 2003). All experimental documents and recordings will be kept for 5 years as is a standard requirement for most publication journals, and will be destroyed after this time.

Results
This research study is based on the entire group's performance, so no individual results will be analysed, published or made available for feedback. Once the group data has been analysed and conclusions have been drawn, you will receive these results.

Future Research Studies
Within the 5 year data retention period, the data may be reanalysed as part of similar studies. However, this data will remain anonymous and confidential, and destroyed after this time.

Permission

This study has received ethical approval from the Research Ethics Committee at AMNCH and at the National University of Ireland Maynooth.

Further Information

You can get more information or answers to your questions about the study, your participation in the study, and your rights, from Dr Ronan Collins at Tallaght hospital (who can be telephoned at 01-4144724), or lead investigator Elizabeth Walshe at NUI Maynooth, Co. Kildare (ph: 0857136153 or email: Elizabeth.walshe.2009@nuim.ie).

If during your participation in this study you feel the information and guidelines that you were given have been neglected or disregarded in any way, or if you are unhappy about the process, please contact the Secretary of the National University of Ireland Maynooth Ethics Committee at research.ethics@nuim.ie or +353 (0)1 708 6019. Please be assured that your concerns will be dealt with in a sensitive manner.

NUI MAYNOOTH
Ollscoil na hÉireann Má Nuad

THE ADELAIDE & MEATH HOSPITAL, DUBLIN
INCORPORATING
THE NATIONAL CHILDREN'S HOSPITAL

SJH / AMNCH & NUIM RESEARCH ETHICS COMMITTEE PARTICIPANT CONSENT FORM

Study title:	*Investigating the Cognitive and Electrophysiological Processes Underpinning Walking Gait and Fall-Risk Post-Stroke.*

This study and this consent form have been explained to me. I believe I understand what will happen if I agree to be part of this study.

I have read this consent form. I have had the opportunity to ask questions and all my questions have been answered to my satisfaction. I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights. I have received a copy of this agreement and I understand that a signed copy will be saved at the National University of Ireland Maynooth.

PARTICIPANT'S NAME:

_____

PARTICIPANT'S SIGNATURE:

_____

Date: _____

Date on which the participant was first furnished with this form: _____

Statement of investigator's responsibility: *I have explained the nature, purpose, procedures, benefits, risks of, or alternatives to, this research study. I have offered to answer any questions and fully answered such questions. I believe that the participant understands my explanation and has freely given informed consent.*

Investigator's signature:_____

Date: _____

Appendix N

SJH / AMNCH RESEARCH ETHICS COMMITTEE
Post-Stroke Patient Information Leaflet

Study title: Investigating the Cognitive and Electrophysiological Processes Underpinning Walking Gait and Fall-Risk Post-Stroke.

Principal investigator's name:	**Dr Ronan Collins**
Principal investigator's title:	Asst. Professor of stroke medicine
Lead Investigator's name:	**Elizabeth Walshe**
Lead Investigator's title:	PhD Research Candidate
Telephone number:	**0857136153**

You are being invited to take part in a research study to be carried out at Tallaght Hospital and Maynooth University.

Before you decide whether or not you wish to take part, you should read the information provided below carefully and, if you wish, discuss it with your family, friends or GP (doctor). Take time to ask questions–don't feel rushed and don't feel under pressure to make a quick decision.

You should clearly understand the risks and benefits of taking part in this study so that you can make a decision that is right for you. This process is known as 'Informed Consent'. You don't have to take part in this study. If you decide not to take part it won't affect your future medical care.

Please contact Elizabeth Walshe at the above details if you would like more information, or wish to volunteer.

You can change your mind about taking part in the study any time you like. Even if the study has started, you can still opt out. You don't have to give us a reason. If you do opt out, rest assured it won't affect the quality of treatment you get in the future.

Introduction

This study is investigating why there is an increased risk for falling in some older adults and post-stroke, what processes in the brain are important for maintaining balance, and

what tasks or measures we can use to predict those at risk and prevent future falls. This study is being carried out by lead investigator Elizabeth Walshe, as part of an academic PhD qualification at the National University of Ireland Maynooth. This research is supervised by Drs. Richard Roche and Seán Commins of NUI Maynooth, and Dr. Ronán Collins of Tallaght Hospital. This project is funded by a PhD scholarship from the Irish Research Council.

Procedures

Why am I being asked to take part?
You were treated at Tallaght hospital for experiencing a Stroke over 6 months ago, are aged over 21 and can walk without assistance (with/without an aid) for at least 10m.

What will participation involve?
All testing will take place in Tallaght hospital at a time that suits you, where you will meet with lead investigator Elizabeth Walshe. The testing session will be a once-off commitment of your time, for an average of 2 hours, and you will be given multiple opportunities to take a short break. Your medical records will be looked at by the researchers, if you consent, to gain information about your diagnosis (such as the area of the brain it affected, how severe it was and other such details pertaining to the stroke event). If you do not consent to the researcher viewing your records, your consultant will gather the information instead. Your testing results will be anonymous, with only an average group result being used academically for publication of the study's findings.

You will be asked to walk normally on a straight pathway for a few minutes while we record your walking movements with two wearable sensors (in some cases a digital video recording may be taken). You will then be asked to complete general questionnaires that will ask you about any previous experience of falls or balance concerns, and pen and paper tasks requiring you to read a list of words, recall some words and numbers, and complete some simple drawings. Computer-based tasks of memory, attention and motor abilities will also be used which will present an auditory tone or visual image, word or number on screen and ask you to respond with a mouse click or key press. As you engage in these tasks, tasks, we will record electrical brain waves by placing a cap on your head which will allow us to record electrical signals from the scalp. This recording procedure (an EEG cap with connecting electrodes and signal-enhancing gel) is akin to measuring your heart-rate or blood-pressure, in that it is completely safe, pain-free and non-invasive.

Benefits

You may not receive any benefit. As this is a research study, we cannot state that you will benefit personally from taking part. However, your participation in this study contributes to our understanding of falls and walking gait impairments in older adults and adults post-stroke. The findings from this study hope to identify if tasks of mental processes could be of use in future fall-risk screening and intervention.

Risks

This research is designed to be safe, pain-free and non-invasive. None of the tasks have been designed to be deceptive or stress-inducing in any way, and do not pose any risk greater than everyday real-world activities. The measurement of brain activity will require you to wear an electrode cap with a special gel to be used on the scalp to enhance the signal. This may require your hair to be washed after the study (these facilities will be provided for you). The gel is designed to be sensitive, but will be tested beforehand to ensure no negative experience. This procedure does not involve radiation, x-rays, magnetic fields or any other dangerous elements. Should you feel any discomfort at any point while taking part, please inform the researcher (Elizabeth Walshe) immediately, and the process can be stopped. The researchers are covered by standard insurance and your doctors are covered by standard medical malpractice insurance. Nothing in this document restricts or curtails your rights.

Exclusion from participation

You may not be eligible to take part if many of these criteria apply to you:
- You are unable to provide consent;
- You are unable to walk at least 10m, with or without an aid (cane, etc.);
- You have severe (uncorrected) visual impairments;
- You have a history of psychological/neurological impairment (before diagnosis);
- You have had a severe head trauma resulting in unconsciousness (before diagnosis);
- You have a history of epilepsy;
- You have been diagnosed with dementia, or moderate to severe aphasia
- You are currently taking psychoactive medication;
- You have other relevant medical conditions (e.g. vestibular/musculoskeletal);
- You have an uncontrolled/unstable blood pressure/heart condition;
- You have a history of drug or alcohol problems;
- You have had a lower limb amputation, recent joint replacement;
- You have severe hemiplegia**;**
- You have had a Labyrinthectomy

Confidentiality

Records

Your identity will remain confidential. Your name will not be published and will not be disclosed to anyone outside the hospital. If you consent, Elizabeth Walshe will check your medical records to ensure you fit the criteria of the study. If you do not consent to this, your medical consultant will access your records instead. Your GP will not be contacted by us about your participation, but we will inform your consultant. If you take part, you will be assigned a code number in place of your name for all experimental documents and

recordings, to ensure anonymity. All information will be stored on secure hard-drives and in locked filing cabinets in the Department of Psychology at the National University of Ireland Maynooth, which may only be accessed by the lead researcher and supervisors (in accordance with the Data Protection Act of 2003). All experimental documents and recordings will be kept for 5 years as is a standard requirement for most publication journals, and will be destroyed after this time.

Results
This research study is based on the entire group's performance, so no individual results will be analysed, published or made available for feedback. Once the group data has been analysed and conclusions have been drawn, you will receive these results.

Future Research Studies
Within the 5 year data retention period, the data may be reanalysed as part of similar studies. However, this data will remain anonymous and confidential, and destroyed after this time.

Stopping the study

You understand that your doctor or the lead investigator may stop your participation in the study at any time without your consent, and that you are free to end your participation immediately at any stage of testing.

Permission

This study has received ethical approval from the Research Ethics Committee at this hospital and at the National University of Ireland Maynooth.

Further Information

You can get more information or answers to your questions about the study, your participation in the study, and your rights, from Dr Ronan Collins at Tallaght hospital (who can be telephoned at 01-4144724), or lead investigator Elizabeth Walshe at the Department of Psychology at NUI Maynooth, Co. Kildare (ph: 0857136153 or email: Elizabeth.walshe.2009@nuim.ie). If your doctor learns of important new information that might affect your desire to remain in the study, he or she will tell you.

If during your participation in this study you feel the information and guidelines that you were given have been neglected or disregarded in any way, or if you are unhappy about the process, please contact the Secretary of the National University of Ireland Maynooth Ethics Committee at research.ethics@nuim.ie or +353 (0)1 708 6019. Please be assured that your concerns will be dealt with in a sensitive manner.

Maynooth University
National University of Ireland Maynooth

THE ADELAIDE & MEATH HOSPITAL, DUBLIN
INCORPORATING
THE NATIONAL CHILDREN'S HOSPITAL

SJH / AMNCH RESEARCH ETHICS COMMITTEE
POST-STROKE PATIENT CONSENT FORM

Investigating the Cognitive and Electrophysiological Processes Underpinning Walking Gait and Fall-Risk Post-Stroke

This study and this consent form have been explained to me. I believe I understand what will happen if I agree to be part of this study.

I have read, or had read to me, this consent form. I have had the opportunity to ask questions and all my questions have been answered to my satisfaction. I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights. I have received a copy of this agreement and I understand that a signed copy will be sent to the National University of Ireland Maynooth.

PARTICIPANT'S NAME:

_____

PARTICIPANT'S SIGNATURE:

_____

Date:_____

Date on which the participant was first furnished with this form:_____

Statement of investigator's responsibility: *I have explained the nature, purpose, procedures, benefits, risks of, or alternatives to, this research study. I have offered to answer any questions and fully answered such questions. I believe that the participant understands my explanation and has freely given informed consent.*

Investigator's signature:_____

Date:_____