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Re-imagining motor imagery: Building bridges between cognitive neuroscience and sport psychology

Aidan Moran[1]*, Aymeric Guillot[2], Tadhg MacIntyre[3] and Christian Collet[2]

[1]University College Dublin, Ireland
[2]Université Claude Bernard Lyon 1, Lyon, France
[3]University of Ulster, Belfast, Northern Ireland

One of the most remarkable capacities of the mind is its ability to simulate sensations, actions, and other types of experience. A mental simulation process that has attracted recent attention from cognitive neuroscientists and sport psychologists is motor imagery or the mental rehearsal of actions without engaging in the actual physical movements involved. Research on motor imagery is important in psychology because it provides an empirical window on consciousness and movement planning, rectifies a relative neglect of non-visual types of mental imagery, and has practical implications for skill learning and skilled performance in special populations (e.g., athletes, surgeons). Unfortunately, contemporary research on motor imagery is hampered by a variety of semantic, conceptual, and methodological issues that prevent cross-fertilization of ideas between cognitive neuroscience and sport psychology. In this paper, we review these issues, suggest how they can be resolved, and sketch some potentially fruitful new directions for inter-disciplinary research in motor imagery.

One of the most remarkable capacities of the mind is its ability to simulate sensations, actions, and other types of experience. For over a century (e.g., see Betts, 1909), researchers have investigated the construct of *mental imagery* or the cognitive simulation process by which we can represent perceptual information in our minds in the absence of appropriate sensory input (Munzert, Lorey, & Zentgraf, 2009). A key feature of this simulation process is that it normally gives rise to the subjective experience of perception – as happens in the case of *seeing* with the mind's eye or *hearing* with the mind's ear (Kosslyn, Thompson, & Ganis, 2006). However, not all forms of imagery elicit such distinctive phenomenological concomitants. For example, Kosslyn, Ganis, and Thompson (2010) noted that spatial imagery (which is essential for the representation of location information) produces only an impoverished sense of

**Correspondence should be addressed to Aidan Moran, School of Psychology, University College Dublin, Belfield, Dublin 4, Ireland (e-mail: Aidan.Moran@ucd.ie).*

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'where things are' (p. 3). Nevertheless, on the basis that different types of perception give rise to correspondingly different forms of imagery (Moulton & Kosslyn, 2009), various types of imagery processes have been identified. For example, cognitive neuroscientists such as Blajenkova, Kozhevnikov, and Motes (2006) distinguished between *visual object imagery* (which involves mental representations of 'the literal appearances of individual objects in terms of their precise form, size, shape, colour and brightness'; p. 239) and *spatial imagery* (which involves the mental representations of 'the spatial relations amongst objects, parts of objects, locations of objects in space, movements of objects and object parts and other complex spatial transformations'; pp. 239–240).

Another mental simulation process that has attracted research interest is 'motor imagery', which may be defined as a dynamic mental state during which the representation of a given motor act or movement is rehearsed in working memory without any overt motor output (Collet & Guillot, 2010). Typically, motor imagery or the 'covert simulation of movement' (Holmes, 2007, p. 1) is evident whenever people imagine actions without engaging in the actual physical movements involved. At the neural level, motor imagery appears to require information processing by the associative parietal cortex, which not only controls force and posture during actual movement but also the formation of body image and its relation to external space (Freund, 2003).

Before we consider the importance of research on motor imagery, however, an important question of terminology needs to be addressed. Specifically, should we refer to this construct as 'motor imagery', 'kinaesthetic imagery', 'movement imagery', or as some combination of these terms? Inspection of the relevant research literature reveals considerable semantic confusion on this issue. For example, some investigators regard 'motor imagery' as being synonymous with 'movement imagery' (e.g., Nam, Jeon, Kim, Lee, & Park, 2011; Roberts, Callow, Hardy, Markland, & Bringer, 2008) or 'imagery of movement' (e.g., Isaac, Marks, & Russell, 1986). Other researchers favour the term 'kinaesthetic imagery' – which refers broadly to our ability to imaginatively sense the position and movement of our bodies (see Proske & Gandevia, 2009, for a review of research on kinaesthesia). For example, Moulton and Kosslyn (2009) postulated that motor imagery is 'actually proprioceptive or kinaesthetic imagery – one experiences the bodily sensations of movement, not the movement commands themselves' (p. 1273). Similarly, Gabbard and Bobbio (2011) claimed that motor imagery is 'also known as kinaesthetic imagery'. More recently, researchers such as Hashimoto, Ushiba, Kimura, Liu, and Tomita (2010) and Hohlefeld, Nikulin, and Curio (2011) have proposed the term 'kinaesthetic motor imagery'. According to the latter investigators, this term designates 'a mental/neuronal simulation of an overt movement without muscle comtraction' (p. 186). Given such a myriad of different terms for this construct, how should we proceed?

In an effort to clarify matters, we propose in the present paper to retain the conventional term 'motor imagery' (Decety, 1996b; Jeannerod, 1994) for three reasons. First, research suggests that it is possible to form a motor image of one's static position (e.g., in an isometric contraction) *without* the rehearsal of a dynamic movement of one's body (Hashimoto *et al.*, 2010). In other words, strictly speaking, motor imagery involves the absence of overt motor *output* rather than of overt movement itself. Next, a search of several dictionaries (e.g., Eysenck, Ellis, Hunt, & Johnson-Laird, 1994) and encyclopaedias (e.g., Magill, 1996; Nadel, 2002) of psychology reveals many entries for 'motor' (e.g., 'motor control and learning', 'motor development') but none for 'movement'. Finally, a keyword search of PsycINFO in May 2011 showed that the term 'motor imagery' was cited *eight times* more frequently in the titles of peer-reviewed papers than was the term 'movement imagery' (with the figures estimated at 184 and 23, respectively).

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Research on motor imagery is important in psychology for a number of theoretical and practical reasons. To begin with, it is crucial to our understanding of motor cognitive processes such as mental rehearsal and movement planning (Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009). Second, it enables researchers to explore the relationship between consciousness and action. Thus, motor imagery research allows investigators to study 'whether conscious thoughts of a particular action can affect whether or how that action will be performed later' (Baumeister, Masicampo, & Vohs, 2011). Third, it helps to rectify a marked imbalance of coverage in imagery research. In particular, although the construct of mental imagery is routinely defined as being multi-sensory (Kosslyn, Seger, Pani, & Hillger, 1990; Moran, 1993; Morris, Spittle, & Watt, 2005), far fewer papers have been published on *motor* imagery than on *visuo-spatial* imagery. To illustrate, a keyword search of PsycINFO in May 2011 shows that almost twice as many peer-reviewed papers have been published with 'visual imagery' in the title (358) as compared with 'motor imagery' in the title (184). Interestingly, a perusal of the subject indices of nine recent textbooks in cognitive psychology (Eysenck & Keane, 2010; Gobet, Chassy, & Bilalic, 2011; Goldstein, 2011; Matlin, 2009; Reed, 2010; Reisberg, 2010; Smith & Kosslyn, 2007; Sternberg, 2009; Whitman, 2011) shows that whereas 'visual imagery' is invariably listed, motor imagery is not. Specifically, of the nine preceding publications, motor imagery appears in the subject index of only two cognitive textbooks – those by Matlin (2009) and Smith and Kosslyn (2007). A fourth theoretical reason for studying motor imagery is that it provides an empirical window through which to investigate action control mechanisms in both the healthy and pathological brain (de Lange, Roelofs, & Toni, 2008). This investigation of action control is important because historically, cognitive psychology has been 'preoccupied with disembodied perceptions . . . and indifferently concerned with translating perceptions and higher processes into "action"' (Adams, 1987, p. 66). Fifthly, motor imagery research enables researchers to explore *embodied* cognition – the idea that cognitive representations are 'grounded in, and simulated through, sensorimotor activity' (Slepian, Weisbuch, Rule, & Ambady, 2011, p. 26; see also Shapiro, 2011, for a detailed review of embodied cognition) or that mental processes that evolved to control action can also be used *off-line* to simulate motor skills and knowledge (Wilson, 2002). To illustrate this latter point, Lorey *et al.*, (2009) proposed that 'body-related experiences also shape processes such as perception or imagery that were formerly conceptualized as purely "cognitive"' (p. 233). Complementing the preceding theoretical reasons for studying motor imagery are certain practical reasons. For example, motor imagery techniques are widely used to enhance skill learning and skilled performance in special populations such as elite athletes (see review by Weinberg, 2008), musicians (Meister *et al.*, 2004), and surgeons (Arora *et al.*, 2010; 2011). Similarly, motor imagery is known to be effective in facilitating the physical rehabilitation of people who have suffered neurological damage (e.g., Braun, Beurskens, Borm, Schack, & Wade, 2006, McEwen, Huijbregts, Ryan, & Polatajko, 2009; Malouin & Richards, 2010).

In view of the preceding evidence, it is not surprising that motor imagery has attracted considerable attention from researchers in disciplines such as cognitive neuroscience (e.g., Carillo-de-la-Peña, Galdo-Alvarez, & Lastra-Barreira, 2008; Guillot *et al.*, 2009; Heremans *et al.*, 2009; Lorey *et al.*, 2009; Munzert & Zentgraf, 2009), sport psychology (e.g., Cumming & Ramsey, 2009; Guillot & Collet, 2008), motor learning (e.g., Golomer, Bouillette, Mertz, & Keller, 2008), and medical and rehabilitation science (e.g., Hovington & Brouwer, 2010; Steenbergen, Crajé, Nilsen, & Gordon, 2009). At first glance, such research interest in motor imagery seems to provide welcome and convincing evidence

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of a thriving field – one that is characterized not only by inter-disciplinary collaboration but also by the use of the latest neuro-imaging technology such as functional magnetic resonance imaging (fMRI; see Olsson, Jonsson, Larsson, & Nyberg, 2008) and transcranial magnetic stimulation (Fourkas, Bonavolontà, Avenanti, & Aglioti, 2008; Li, Stevens, & Rymer, 2008). However, on closer inspection of the relevant research literature, it is evident that, apart from the terminological confusion illustrated earlier, there are significant conceptual and methodological barriers to the integration of motor imagery research findings between the two dominant disciplines in this field – cognitive neuroscience and sport psychology.

At the conceptual level, consider a problem at the heart of many neuroscientists' understanding of motor imagery – the idea that this construct is synonymous with only one of two possible visual imagery perspectives. To explain what we call this 'limited perspective' problem, some background information is required. Briefly, for many years, imagery researchers have distinguished between a 'first-person' visual perspective (whereby people imagine themselves performing a given action) and a 'third-person' visual perspective (whereby people imagine seeing either themselves or someone else performing the action) (Fourkas, Avenanti, Urgesi, and Aglioti, 2006). Interestingly, this distinction between two types of visual perspective for the representation of motor information is analogous to that between 'egocentric' and 'allocentric' frames of reference for the representation of spatial information (Klatzky & Wu, 2008). To explain, this latter information 'could be represented *egocentrically* based on an origin centred on the observer, or it could be represented *allocentrically,* based on the encoding of interobject relations and metric distances and angles within the scene itself' (Carlson, Hoffman, & Newcombe, 2010, p. 573). Unfortunately, a number of cognitive neuroscience researchers appear to regard motor imagery as being synonymous with only one of the two preceding visual perspectives – namely, the *first-person* one. For example, Decety (1996a) suggested that motor imagery 'corresponds to the so-called internal imagery (or first-person perspective) of sport psychologists' (p. 87). This idea was endorsed by Jeannerod (1997) who distinguished between visual or *third-person* perspective imagery and motor imagery, which is 'experienced from within, as the result of a 'first-person' process, where the self feels like an actor rather than a spectator' (p. 95). Similarly, Romero, Lacourse, Lawrence, Schandler, and Cohen (2000) defined motor imagery as 'the mental representation of one's self performing a motor act without overt movement' (p. 83) and Lorey *et al.* (2009) regarded it as 'an internal rehearsal of movements from a first-person perspective without any overt physical movement' (p. 233). Likewise, Hovington and Brouwer (2010) claimed that motor imagery requires 'that individuals are able to visualize themselves performing the task from the first-person perspective' (p. 851) and Gueugneau, Crognier, and Papaxanthis (2008) postulated that 'during motor imagery subjects feel themselves performing a movement (first-person perspective) without moving the limbs involved' (p. 95). Although the preceding definitions are plausible intuitively, they are contradicted by empirical evidence. For example, as Fourkas *et al.* (2006) pointed out, people can form motor images using either a first-person or a third-person perspective. Indeed, there is evidence from qualitiative studies (Moran & MacIntyre, 1998), descriptive research (e.g., Callow & Hardy, 2004; Callow & Roberts, 2010), and experiments (e.g., Hardy & Callow, 1999) in sport psychology that motor imagery representations can be accessed consciously using a third-person visual perspective. For example, Hardy and Callow (1999) investigated the effects of different imagery perspectives on the performance of tasks involving form-based

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movements (e.g., a gymnastic floor routine). Results showed that an 'external' (third-person) visual imagery perspective was superior to an 'internal' (first-person) perspective in facilitating performance of such movements. Although the preceding evidence on motor imagery formation from different perspectives is persuasive, however, it is not conclusive. To explain, in order to demonstrate a robust link between motor imagery and a third-person imagery perspective, researchers require evidence that participants actually adhere to experimental instructions employing this perspective and that such instructions elicit reliable activation in the cerebellum and supplementary motor cortex (see Naito *et al.*, 2002). Clearly, this latter evidence is still awaited.

Turning to the methodological level, differences are apparent between cognitive neuroscientists and sport psychologists in the rigour with which participants' imagery experiences are validated during experiments. To illustrate, whereas neuroscientists such as Lotze and Halsband (2006) admitted 'that ... a precise control of *what the subject actually does during imagery* remains an illusion' (p. 389) [our italics], manipulation checks on the instructions to, and experiences of, participants are routinely used by imagery researchers in sport psychology (Cumming & Ramsey, 2009; Nordin & Cumming, 2005). Such manipulation checks are crucial prerequisites of the validity of experimental research (Goginsky & Collins, 1996). Unfortunately, some neuroscientific studies of motor imagery are flawed by potentially confusing instructions. For example, Olsson *et al.* (2008) used fMRI technology to investigate how 'internal' (first-person) imagery training affects neural activity. These researchers indicated that 'all through the instruction, an internal perspective was emphasised ... the participants understood that it was important to "feel" like the high jump was executed with no muscular movement *and not to "see" that the high jump was executed*' [p. 6 (italics added)].[1] In the absence of manipulation checks on imagery compliance, how can we be sure that participants did not 'see' themselves executing the high jump? This latter scenario is also possible given the fact that avoidant instructions can sometimes produce counter-intentional effects (e.g., Russell & Grealy, 2010; Wegner, 1994).

Taken together, these conceptual and methodological problems in neuroscientific studies of imagery hamper integration of findings with those obtained from sport psychology and impede progress in understanding the theoretical mechanisms underlying motor imagery processes. Therefore, the purpose of the present paper is to review some key barriers that divide motor imagery researchers in cognitive neuroscience from their counterparts in sport psychology, suggest how they can be overcome, and sketch some potentially fruitful new directions for increased interdisciplinary research in this field.

In order to achieve our objectives, the paper is organized as follows. First, we shall attempt to identify and resolve some confusion in cognitive neuroscience with regard to experimental instructions used to elicit motor imagery processes. After that, we shall evaluate some differences between the ways in which motor imagery researchers in cognitive neuroscience and sport psychology have interpreted the theoretical bridge between their disciplines – namely, the 'functional equivalence' hypothesis or the seminal proposal that motor imagery and motor preparation and execution share some neural substrates (Beilock & Lyons, 2009; Decety, 1996a). Next, we shall argue that mental-chronometry techniques (i.e., those in which the time-course of information processing activities is used to draw inferences about cognitive mechanisms; Ward, 2010) are relatively under-utilized in cognitive neuroscience despite the valuable insights

[1] *Although we acknowledge the value of combining kinaesthetic and visual imagery instructions in this ecologically rich study, we are concerned that the absence of a manipulation check may impair accurate interpretation of results.*

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that they can provide into motor imagery processes. Finally, we shall draw relevant conclusions and sketch some potentially fruitful new directions for interdisciplinary (neuroscience/sport psychology) research in motor imagery.

The problem of a limited perspective: Experimental instructions and motor imagery processes

In the previous section, we highlighted what we called the 'limited perspective' problem in motor imagery research in cognitive neuroscience – namely, the assumption that this construct is synonymous with a first-person visual perspective only. In the present section, we investigate how this problem, and other related issues, may lead to contamination of the experimental instructions used to elicit motor imagery processes in some studies in this field.

To begin with, consider a study by Sirigu and Duhamel (2001). These investigators used instructions that had been phrased to generate mental images of a hand-rotation task either in a 'first-person' or 'third-person' perspective, assuming that such instructions elicited motor and visual imagery, respectively. However, as we have indicated, sport and motor skill researchers have shown that a kinaesthetic imagery representation can be accessed through a third-person perspective (Hardy & Callow, 1999; Murphy, Nordin, & Cumming, 2008). In fact, based on correlational evidence obtained from people's performance on two standardized movement imagery scales, Callow and Hardy (2004) reported that 'for movements in which form is an important component, kinaesthetic imagery has a stronger association with external visual imagery than internal visual imagery' (p. 174). Furthermore, the motor skills literature has extensively reported selective differences in motor performance and motor learning following various types of imagery. Based on these findings, and even though first-person visual imagery perspective and kinaesthetic imagery may be easily combined, future research should state more clearly whether the participants are required to associate or dissociate these two forms of mental imagery, depending upon the nature of the task (e.g., spatial or allocentric representations focused on inter-object relationships and relative position among objects and persons, on the one hand, and bodily or egocentric representations, on the other hand).

Next, methodological issues arise more generally from the vagueness of many instructions given to participants in imagery studies. To explain, many cognitive neuroscientific studies of motor imagery cannot be replicated easily because they fail to provide sufficient information about the nature of the motor task and/or about the type and content of imagery being performed. For example, a number of studies (e.g., Abbruzzese, Assini, Buccolieri, Marchese, & Trompetto, 1999; Bakker *et al.*, 2008; Beisteiner, Höllinger, Lindinger, Lang, & Berthoz, 1995; Cramer, Orr, Cohen, & Lacourse, 2007; Fadiga *et al.*, 1999; Gardini, de Beni, Cornoldi, Bromiley, & Venneri, 2005; Harrington, Farias, Davis, & Buonocore, 2007; Kasess *et al.*, 2008; Kuhtz-Buschbeck *et al.*, 2003) fail to explain to the reader exactly what task has been performed during motor imagery conditions as compared to what happens in control or non-specific visual imagery conditions. Simply stating that the participants were required to 'imagine the movements' (e.g., Caeyenberghs *et al.*, 2009, p. 477) is not sufficient to enable precise replication of such studies. Furthermore, we need to know exactly how the investigators ensured that participants actually complied with the experimental instructions to use a first- or a third-person perspective.

Unfortunately, even when details of imagery instructions are supplied by researchers, clarity is not always evident. For example, consider the instructions used by Fourkas *et al.* (2008) that purport to induce an 'internal' imagery perspective in participants:

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'Imagine yourself on a golf course at the teeing-off area starting the shot. The shot should be a long shot, well played, and with the correct direction which easily reaches the green. Imagine yourself having this shot replayed several times. Try to focus on the feel of your hands holding the handle of the club, as if the club is the natural extension of your arm, and the club and hand are integrated into one thing' (p. 2,389). Here, the instructions to adopt a first-person imagery perspective are potentially confounded by the request to imagine a shot that '*easily reaches the green*' – a phrase that presumably elicits visual object imagery from a third-person perspective.[2] More generally, it is important for studies in this field to contain precise information about the type of imagery perspective used by participants.

Interestingly, recent data suggest that different types of imagery elicit different types of neural activation (Guillot *et al.*, 2009; Jackson, Meltzoff, & Decety, 2006; Ruby & Decety, 2001; Solodkin, Hlustik, Chen, & Small, 2004). Specifically, visual and kinaesthetic imagery appear to be mediated by separate neural networks (Solodkin *et al.*, 2004; Guillot *et al.*, 2009). Furthermore, imagery perspective also appears to have reliable neural substrates. For example, Lorey *et al.* (2009) reported that imagery of a hand-movement from a first-person perspective elicits greater activity in motor-related structures of the brain than does imagining this movement from a third-person perspective. Despite the preceding evidence on the separate processing of visual and kinaesthetic cues, however, motor imagery is typically reported as an integrated experience in neuroscientific studies.

In an effort to resolve the preceding confusion about the experimental elicitation of motor imagery processes, three suggestions seem relevant. First, future researchers need to distinguish between *kinaesthetic* imagery and the imagination of movement *per se*. Kinaesthetic imagery requires the ability to mentally simulate physical movement through muscle contractions and stretching, joint amplitude and load whereas the imagination of movement may be undertaken from either of the two visual imagery perspectives discussed previously. Second, in order to avoid unnecessary confusion between kinaesthetic imagery and *internal* visual imagery, researchers should provide precise experimental instructions for participants that explain exactly what movements should be imagined and which visual perspective to use in doing so. Such precision is important if we are to avoid potentially confusing instructions. For example, as mentioned in the previous section, Olsson *et al.* (2008) investigated whether or not 'internal' (first-person perspective) imagery might be effective in enhancing high-jump performance. Unfortunately, the instructions that these researchers actually used requested the participants to *combine* spatial (clearing the bar), visual (visualizing the entire high jump from beginning to end), and kinaesthetic (feeling one's knee position) imagery, hence making it difficult to interpret the results unambiguously. Finally, for reasons explained earlier, imagery researchers need to use manipulation checks to validate their experimental instructions.

Evaluating the 'functional equivalence' hypothesis in motor imagery research

Until the 1980s, the theoretical mechanisms underlying mental imagery were largely unknown. However, important progress in addressing this issue occurred with the

[2] *Although kinaesthetic imagery may be elicited by instructions to adopt either a first-person or a third-person perspective, it is important for experimental control to know precisely which one of these perspectives participants actually used.*

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discovery that imagery shares some neural pathways and mechanisms with like-modality perception (Farah, 1984; Kosslyn, 1994) and also with the preparation and production of movements (Decety & Ingvar, 1990; Jeannerod, 2001). In short, there are close parallels between perceiving, imagining, and motor control (planning and executing actions). Recognition of these parallels led to the 'functional equivalence' hypothesis (e.g., Finke, 1979; Jeannerod, 1994) or the proposition that cognitive simulation processes (e.g., imagery) share, to some degree, certain representations, neural structures, and mechanisms with like-modality perception and with motor preparation and execution processes. For example, neuro-imaging studies show that mentally simulated and executed actions rely on similar neural representations and activate many common brain areas such as the posterior parietal, pre-motor, and supplementary motor cortex (de Lange *et al.*, 2008; Munzert *et al.*, 2009). Based on such evidence, motor imagery processes are often regarded as a 'scaled-down' version of the same processes that occur during execution of overt movements (but see Hohlefeld *et al.*, 2011).

A key proponent of functional equivalence was Johnson (1982) who investigated the effects of imagined movements on the recall of a learned motor task and concluded that 'imagery of movements has some functional effects on motor behaviour that are in some way *equivalent* [emphasis added] to actual movements' (p. 363). Later, Decety and Ingvar (1990) proposed that mental practice (or the systematic use of motor imagery to rehearse an action covertly before physically executing it; Driskell, Copper, & Moran, 1994) is a 'virtual simulation of motor behaviour' (p. 26). They also postulated that motor imagery 'requires the construction of a dynamic motor representation in working memory which makes use of spatial and kinaesthetic components retrieved from long-term memory' (p. 26; see also Decety, 2002). Also, Grèzes and Decety (2001) suggested that there is 'a functional equivalence between intending, simulating, observing, and performing an action' (p. 1). Other experimental studies in the visual modality (e.g., Roland & Friberg, 1985) suggested a functional equivalence between imagery and perception because 'most of the neural processes that underlie like-modality perception are also used in imagery' (Kosslyn, Ganis, & Thompson, 2001, p. 641). In cognitive sport psychology, an early advocate of the functional equivalence hypothesis was Moran (1996) who, in reviewing theories of mental practice, suggested that mental imagery is 'a covert simulation of perceptual experience and that as a consequence, imagery and perception share certain processing resources' (pp. 216–217).

The functional equivalence hypothesis is supported both by neuroscientific evidence [e.g., psychophysiological data obtained using event-related potentials (ERPs); see Carillo-de-la-Peña *et al.*, 2008] and by experimental research findings (e.g., Finke, 1979). To illustrate the former, research shows that there is a great deal of overlap between the neural substrates of physical and imagined movement execution. Specifically, motor imagery and movement execution activate such neural regions as pre-motor cortex, primary motor cortex, basal ganglia, and cerebellum (Jeannerod, 2001) as well as the inferior frontal gyrus and supplementary motor area (Kühn, Bodammer, & Brass, 2010). Additional evidence in this regard comes from Miller *et al.* (2010) who found that the spatial distribution of local neural activity during motor imagery mimics that occurring during actual motor movement. Also, imagined and executed actions tend to activate associated psycho-physiological systems to similar degrees (for review, see Collet & Guillot, 2010). For example, Decety, Jeannerod, Durozard, and Baverel (1993) as well as Wuyam *et al.*, (1995) found that heart rate and pulmonary ventilation tend to increase during imagined actions (Witt & Proffitt, 2008).

Functional equivalence does not necessarily imply functional *identity*, however (Carillo-de-la-Peña *et al.*, 2008). Thus, the neural substrates of motor imagery do no match exactly those of actual movement execution. For example, Carillo-de-la-Pena *et al.* (2008) found that there were significant differences between the ERPs elicited during motor imagery and those obtained during motor execution. Also, there are a number of brain areas that show increased activation while participants are engaged in imagery of a skill but not during its actual performance (e.g., see Hanakawa *et al.*, 2003) The converse also appears to be true. Thus, there are certain brain areas that are activated during physical performance but not during imagery (Hanakawa *et al.*, 2003).

Experimental evidence provides additional support for a functional equivalence between imagined and executed actions. In other words, motor images appear to share some of the characteristics (e.g., kinematic properties) of corresponding overt movements (Jeannerod, 1994). For example, research using the mental chronometry paradigm (explained in the next section) indicates that there is a close correspondence between the time required to imagine skills/movements and the time required to actually execute them (for review, see Guillot & Collet, 2005a; Guillot, Louis, & Collet, 2010). To illustrate, research shows that people take just as long to physically walk to a given target as they do to imagine walking to that target (Decety, Jeannerod, & Prablanc, 1989; Papaxanthis, Schieppati, Gentili, & Pozzo, 2002). If the task is made more difficult by asking participants to carry a heavy rucksack while they walk, they tend to overestimate the duration of the imagined motion. Therefore, Fitts's Law (Fitts, 1954), which claims that more difficult movements take more time to produce than do easier movements, also appears to apply to imagined actions (Decety & Jeannerod, 1996). Despite such evidence, however, a recent study by Walsh and Rosenbaum (2009) casts doubt the degree of functional equivalence between imagined and executed movements. Briefly, these researchers investigated whether or not motor imagery bears a 'first-order isomorphic relationship' to (or is virtually the same as) actual movements. Participants were asked to indicate which of two possible actions they preferred either by performing the preferred action or by indicating which action they would prefer to perform. Walsh and Rosenbaum (2009) predicted that if motor imagery bears a first-order isomorphism to actual physical actions, then the participants' choices would be the same in both conditions. In other words, 'deciding how to act should not differ from deciding how one *would* act' (p. 1488). However, results showed that this was not the case – thereby challenging the assumption that internal simulations bear a first-order isomorphic relationship to actual motor performance.

Given its origins in research on motor simulation, the functional equivalence hypothesis offers a bridge between cognitive neuroscience and imagery research in sport psychology (Moran, 2009). For example, influenced, in part, by findings that motor imagery and motor control share certain neural representations and pathways, Holmes and Collins (2001) developed the PETTLEP model of motor imagery. This model attempts to understand 'the relationship between the motor imagery and the movement it represents, and the way in which this relationship may be exploited for optimum effect' (p. 61). In pursuit of these objectives, the PETTLEP model postulates a theoretically based checklist for the effective implementation of motor imagery interventions in sport. The term 'PETTLEP' is an acronym, with each of the seven letters representing a key practical issue to be considered when designing imagery scripts and implementing imagery interventions for optimal efficacy in sport. Specifically, these issues are *p*hysical, *e*nvironmental, *t*ask, *t*iming, *l*earning, *e*motional, and *p*erspective. Thus 'P' refers to the athlete's physical response to the sporting situation – which includes his or her

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stance and the equipment used when performing a given skill. 'E' is the perceived physical environment in which the imagery is typically performed, 'T' is the imagined task (which is recommended to be as close as possible to the actual skill to be executed), the next 'T' refers to timing – or the pace at which the imagery is performed, 'L' is a learning or memory component of imagery, 'E' is the emotions elicited by the imagery, and 'P' designates the type of visual imagery perspective used by the practitioner (either first-person or third-person). Overall, the PETTLEP model proposes that motor imagery intervention programmes should endeavour to replicate key behavioural and experiential aspects of the athletes' sporting environment. Thus, in testing this model, Smith and Wright (2008) proposed various practical ideas to 'enhance the physical dimensions of an athlete's imagery. These include using the correct stance, holding any implements that would usually be held, and wearing the correct clothing' (p. 145). Furthermore, in accordance with Lang's (1979) bio-informational theory, the PETTLEP model recommends that imagery scripts should include propositions representing stimulus information (i.e., descriptions of relevant stimuli in the environment), response information (i.e., descriptions of the cognitive, affective, and behavioural responses of the person to relevant stimuli), and meaning information (i.e., the perceived importance of the sport situation to the actor) (see Cumming & Ramsey, 2009).

The PETTLEP approach has made an important contribution to imagery research in sport psychology in at least two ways. To begin with, it was the first evidence-based account of mental imagery to adopt a neuroscientific rationale (by citing the functional equivalence hypothesis). In addition, even though 'the model is far from complete' (Holmes & Collins, 2001, p. 71), it explicitly addresses motor imagery processes as distinct from other types of mental imagery. Although its predictions have not been tested extensively to date, the PETTLEP model has received some empirical support. For example, Smith, Wright, Allsopp, and Westhead (2007) compared the use of PETTLEP imagery training with traditional mental practice techniques and also with physical practice in developing gymnastics jump skills. Results showed that the PETTLEP group improved its proficiency in these skills, whereas the traditional imagery group did not. Also, Wright and Smith (2009) reported that an imagery intervention based on PETTLEP principles led to improvements in a strength task (bicep curls), especially when combined with physical practice. Despite such evidence, the PETTLEP model – or perhaps more accurately, the research that has tested it – is hampered by significant conceptual confusion concerning the meaning and explanatory power of 'functional equivalence'. For example, Wright and Smith (2009) defined this latter idea as 'the principle that imagery enhances performance because the same neurophysiological processes underlie imagery and actual movement' (p. 18). This definition is questionable because it goes beyond available neuroscientific evidence in claiming that the neural substrates of motor imagery and movement execution are *identical* rather than being partly shared. Similarly, consider the claim by Ramsey, Cumming, and Edwards (2008) that 'the degree of equivalence between the imagery experience and the physical experience is a major determinant of imagery's effectiveness at modulating behaviour' (p. 209). This claim can be challenged two grounds. First, it is inaccurate to postulate that functional equivalence occurs at the phenomenological level – between the 'experience' of imagining a skill or movement and that of performing it. Recall that Finke (1979) and Jeannerod (1994) specified that the hypothesized equivalence occurs at the *neural* and/or *mental representational* levels, not at the *phenomenological* level. Clearly, imagining a boxing match or a marathon does not make one feel as tired or as sore as if one actually competed in such events. Logically, in confusing phenomenological

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with representational levels of analysis, Ramsey *et al.* (2008) appear to have made a 'category mistake' (Ryle, 1949) – a conceptual error that occurs when concepts are allocated 'to logical types to which they do not belong' (p. 19). For Ryle (1949), a category mistake occurs when we represent 'the facts of mental life as if they belonged to one logical type or category . . . when they in fact belong to another' (p. 16). The second reason for challenging the preceding statement by Ramsey *et al.* (2008) is that there is no agreed index of 'degree of equivalence' in the relevant scientific literature. This apparent misunderstanding of functional equivalence is also evident in Cumming and Ramsey's (2009) suggestion that 'imagery more functionally equivalent to actual performance will have more pronounced effects on subsequent performance compared to less functionally equivalent imagery' (p. 20). Again, the problem with this claim is that there is no independent measure of the 'amount' of functional equivalence that exists between motor imagery and motor production. Overall, some proponents of the functional equivalence approach in sport psychology appear to have interpreted this term at the *phenomenological* level rather than at the neural/representational level. This problem is unfortunate because, as Murphy *et al.* (2008) remarked recently, a key challenge for imagery researchers in sport psychology is 'to develop a comprehensive model that will guide imagery investigations' (p. 298). Similar sentiments were expressed by Morris (2010) who bemoaned the lack of a 'well founded theory' (p. 488) of mental imagery. Clearly, to develop such a theory requires not only precise use of key terminology (e.g., functional equivalence) but also a thorough understanding of the mechanisms underlying imagery as a *representational* system rather than as an experiential phenomenon. In summary, in order to enhance it theoretical contribution, the PETTLEP model requires clarification and empirical validation by motor imagery researchers in cognitive neuroscience as well as by those in sport psychology.

Importance of mental chronometry in studying motor imagery

Earlier in this paper, we explained that mental chronometry involves the study of the temporal sequencing of information processing activities in the human brain. Influenced by the pioneering work of Donders (1969) and Posner (1978, 2005) in this field, researchers have used chronometric indices of task performance to explore key properties of mental imagery. For example, consider the image-scanning paradigm developed by Kosslyn (1973; see also review by Denis & Kosslyn, 1999) that has been used to investigate the degree to which distance information is preserved accurately in mental images.

In this paradigm, participants who have learned a visual configuration are requested to reconstruct it in their minds and then mentally scan across their image of it. Typical results show that measures of scanning time between selected points on these configurations correlate significantly with the actual distances between such landmarks in the original configuration. This research is important because it shows that there is a structural isomorphism between mental images and the objects that they represent such that topological relationships between parts of objects and detailed metric information (e.g., relative distance between objects) are preserved in imagery (Denis, 2008). Applying this paradigm to motor behaviour, Kosslyn, Ball, and Reiser (1978), Parsons (1987), and Decety *et al.* (1989) measured the temporal congruence between the real and imagined execution of various tasks. For example, Parsons (1987) showed people a photograph of a hand in a given orientation and asked them to judge whether it was a right or a left

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hand. Results showed that the time taken to make a judgement in this task correlated positively with the time taken to rotate one's hand into a given stimulus posture. In short, mental simulation time mimicked actual movement time.

Using the mental chronometry paradigm, imagery researchers have shown that the temporal congruence between actual and imagined times can provide a powerful and reliable assessment of imagery accuracy (for reviews, see Guillot & Collet, 2005a, 2005b; Malouin, Richards, Durand, & Doyon, 2008). Interestingly, evidence of the *difficulty* of preserving the temporal characteristics of a given movement during imagery has yielded important insights into imagery impairments in patients suffering from cortical damage (Sirigu *et al.*, 1996; Malouin, Richards, Desrosiers, & Doyon, 2004). In general, a large volume of experimental studies on athletes has demonstrated that the preservation of the temporal characteristics of movement during imagery is a reliable index of motor imagery accuracy. For example, Louis, Guillot, Maton, Doyon, and Collet (2008) showed that variations of imagery speed may elicit unexpected rapid modifications of the actual speed both in novices and expert athletes – even when the motor task is memorized and controlled for years. Accordingly, these authors showed that a voluntary increase in imagery speed led to increases in the speed of motor performance. Conversely, a voluntary decrease in imagery speed resulted in decreases in the speed of the actual movement. Note, however, that there are some instances where slow/fast imagery might still be beneficial to performers, such as during the early stages of motor learning where slow imagery is useful for helping athletes to assimilate key components of the motor task. Another complication from the research literature is that there is evidence (Calmels, Holmes, Lopez, & Naman, 2006) that total time measures are not always appropriate when assessing the congruence between actual and imagined execution of complex movements (e.g., a gymnastics vault).

Given the importance of motor imagery processes in explaining temporal aspects of performance, research is urgently required to establish the degree to which imagery training could improve the timing skills of athletes. Despite such evidence on the importance of timing processes in athletes, imagery researchers in cognitive neuroscience appear to have generally overlooked the potential value of the chronometric approach in their studies.

Chronometric methods are potentially useful in motor imagery research in cognitive neuroscience. To illustrate, Heremans, Helsen, and Feys (2008) used eye-movement recordings to demonstrate that the coupling between neural patterns for eye and hand movements remained intact when hand movements were merely imagined as opposed to physically being executed. Such a finding offers strong support for the hypothesis that internal representations are processed in a similar way to perceptual stimuli. However, this research would have benefited from a further comparison between imagined and physical times. Although Heremans *et al.* (2008) suggested that eye movements may be used as a real-time index to verify that the participants actually perform motor imagery, this conclusion is hindered somewhat by the lack of information regarding the necessary temporal equivalence between motor performance and motor imagery. Another study by Deutschländer *et al.* (2009) dealt with the use of accurate motor imagery in blind participants. These authors provided evidence that sighted and blind participants used different strategies for locomotion. Interestingly, the former yielded more activation in the visual areas and the ventral stream, while the latter recruited more extensively the somato-sensory cortex and relied on vestibular information for locomotion control. Unfortunately, Deutschländer *et al.* (2009) did not collect any data on people's ability to imagine their performance in real time – information that may

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have provided useful information about the effectiveness of imagery in each case. Lack of consideration of imagined times is also evident in a study by Mulder, Hochstenbach, van Heuvelen, and den Otter (2007) that aimed to investigate the degree to which the ability to imagine movements is affected by age. The authors reported that although no significant general decline in motor imagery ability was apparent, there was evidence of a slight switch from the first-person to third-person imagery perspective across the years. Unfortunately, although Mulder *et al.* (2007) used validated imagery tests [e.g., the Vividness of Movement Imagery Questionnaire (VMIQ); Isaac *et al.*, 1986] to measure imagery vividness, they did not consider the temporal dimension of imagery at all – even though these phenomena are known to be somewhat variable in the elderly (Raz, Briggs, Marks, & Acker, 1999).

To summarize, in order to overcome the preceding limitations in neuroscientific studies on motor imagery, we recommend that future researchers should augment standardized imagery tests (which provide only static snapshots of imagery skills) with chronometric measures. These measures have two key benefits. First, they are valuable in helping researchers to determine the conditions that either increase or reduce the temporal congruence between imagined and executed actions (see Guillot & Collet, 2005a). In addition, chronometric measures, if taken at several intermediate stages during skill learning, can provide insights into the development of motor imagery processes over time.

Building bridges: Conclusions and future directions for research

In this paper, we argued that the construct of motor imagery offers researchers in cognitive neuroscience and sport psychology a fertile field for interdisciplinary research on mental simulation processes. However, we also argued that the cross-fertilization of theories and techniques between these two disciplines is currently impaired by a combination of conceptual and methodological barriers. Specifically, we showed that motor imagery research in cognitive neuroscience is hampered by confusion surrounding the definition of this construct and by inadequate manipulation checks on the experimental instructions purporting to elicit motor imagery processes in participants. Similarly, we argued that motor imagery research in sport psychology lacks theoretical clarity – as is especially evident in the confusion and inconsistency surrounding interpretation of the principle of functional equivalence by investigators in this field. Having recommended that greater use should be made of chronometric measures of motor imagery in both fields (but especially in cognitive neuroscience), we shall now draw two main conclusions and offer some suggestions to facilitate greater integration of research methods and findings between these two disciplines.

Our first conclusion is that the construct of motor imagery requires urgent and systematic conceptual clarification by researchers in both cognitive neuroscience and sport psychology. Such clarification is necessary for at least three reasons. To begin with, it is required because of the semantic confusion generated by the profusion of terms (e.g., 'kinaesthetic imagery', 'movement imagery', 'kinaesthetic motor imagery') designating motor imagery processes (see earlier discussion of this issue). Second, conceptual clarification of motor imagery is necessary because of the 'limited perspective' problem (explained earlier) – the assumption that this construct is synonymous with a first-person visual perspective only. Not surprisingly, this latter problem threatens the validity of the experimental instructions used to elicit motor imagery processes. In this

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regard, cognitive neuroscientists and sport psychologists need to pay more attention to the content of, and manipulation checks on, their imagery scripts. Interestingly, Munzert *et al.* (2009) postulated that different types of imagery instructions can elicit different types of attentional focus and hence, different patterns of neural activation in participants. Therefore, we support their conclusion that motor imagery researchers 'need to analyse the contents of imagery instructions in a more subtle way' (p. 320) than at present. A third reason for conceptual clarification of motor imagery stems from the need to address the theoretical relationship between this construct and related cognitive processes such as observation. In this regard, Holmes and Calmels (2008, 2011) have recently provided interesting reviews of the neuroscientific substrates of, and theoretical relationship between, imagery and observation. Clearly, additional research on this topic is required.

Our second conclusion in this paper is that researchers from cognitive neuroscience and sport psychology have much to learn from each other about the theoretical mechanisms underlying motor imagery. To illustrate, consider the fact that until recently (e.g., Cross & Ticini, 2011), neuroscience has had relatively little impact on theoretical understanding of how dancers learn to create and memorize sophisticated anatomical motor images involving body posture and alignment (e.g., see studies by Hanrahan & Vergeer, 2000; Nordin & Cumming, 2005). This gap in understanding is due, in part, to the tendency for neuroscientists studying motor skills to use simple laboratory tasks (usually involving constrained movements of the fingers) that are chosen not only for their amenability to computational modelling but also for the ease with which they can be mastered after a relatively small amount of practice (Yarrow, Brown, & Krakauer, 2009). However, emerging evidence suggests that when such tasks are replaced by more challenging activities involving multiple effectors, richer insights into motor imagery processes may be obtained. For example, a recent study by Daprati, Nico, Duval, and Lacquaniti (2010) has implications for understanding the motor imagery processes that may underlie dancers' movement expertise. Briefly, these researchers investigated motor imagery processes in stroke patients with varying levels of motor impairment. In particular, they asked these patients, along with a sample of age-matched controls, to perform three activities that require motor imagery processes – a simulated grasping task and two others involving handedness judgements. Results showed that although all patients performed these activities correctly, only those with milder motor impairments appeared to have used mental simulation processes during task performance. In addition, it emerged that stroke patients with severe motor impairments tended to avoid mentally simulating those actions that they could no longer perform. Instead, these latter patients used alternative mental strategies to complete these tasks. These findings led Daprati *et al.* (2010) to conclude that motor imagery is 'more complex a phenomenon than previously understood' (p. 1028) and that it probably involves two separate sets of cognitive skills – 'a true mental simulation of the real action, *and a more creative process that could include manipulating the visual representation of the action, making inferences based on non-motor cues, or retrieving motor memories*' [p. 1,028 (italics added)]. These latter processes may underlie the ability of dancers and athletes to invent and perform novel motor patterns like those reported by Nordin and Cumming (2005). Interestingly, at a more general level, there are signs of a recent paradigm shift in motor cognition research in cognitive neuroscience. Specifically, as well as studying cognitive deficits in clinical populations (e.g., people with brain damage), neuroscientists have begun to adopt a 'strength-based' approach (Moran, 2009) in investigating the neural substrates of expert performers in sport (Aglioti, Cesari, Romani, & Urgesi, 2008; Nakata,

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Yoshie, Miura, & Kudo, 2010; Wei & Luo, 2010; Yarrow *et al.*, 2009). In order to achieve greater integration between motor imagery research in cognitive neuroscience and that in sport psychology, two suggestions are offered – the first theoretical and, the second, methodological.

Theoretically, a potentially valuable new direction for imagery researchers in cognitive neuroscience and sport psychology concerns the investigation of the neglected but important topic of 'meta-imagery processes' – or people's knowledge of, and control over, their own mental imagery skills and experiences (Moran, 2002; for review, see MacIntyre & Moran, 2010). This topic is important because it has implications for theoretical understanding of the function of imagery – an issue that has attracted recent attention from Moulton and Kosslyn (2009). In a seminal paper on meta-imagery, Denis and Carfatan (1985) explored what a sample of undergraduate students knew about imagery research findings in psychology. They presented participants with a 15-item questionnaire and asked them to use their tacit knowledge to predict the outcomes of various imagery experiments that were described but not formally named (e.g., 'is memory for pictures better than memory for words'?). They also asked participants to interpret certain experimental results from imagery studies (e.g., 'can the structure of mental images be said to reflect the spatial organization of the objects they refer to'?). Results showed that although the majority of participants predicted correctly that imagery would have beneficial effects on learning and reasoning, few people were able to predict accurately the results of mental rotation experiments (whereby more time is required to accomplish greater amounts of rotation of images) or mental scanning studies (whereby longer distances between points in an image take longer to scan than shorter distances). Furthermore, a majority of participants regarded as implausible the idea that mental imagery could enhance the performance of motor skills. This latter finding led Denis and Carfantan (1985) to conclude 'how counterintuitive the idea is that motor skills may be affected by purely mental practice' (p. 56). Turning to meta-imagery processes in sport, researchers (e.g., Munroe, Giaccobi, Hall, & Weinberg, 2000; MacIntyre & Moran, 2007a, 2007b) have asked athletes to indicate why, where, how, what, and when they use mental imagery processes. As yet, however, these disparate studies have not been integrated into a coherent theory of meta-imagery processes in athletes. Nevertheless, meta-imagery research has some important implications for cognitive neuroscience. For example, cognitive researchers do not typically select individuals on the basis of their knowledge and/or their use of imagery and, furthermore, do not always control the content of the mental images that are generated by the participants, but simply evaluate their imagery ability through validated (but sometimes quite subjective) psychological questionnaires. We propose that all these aspects should be formally considered in future experimental designs to ensure better control of the individual characteristics and abilities of the participants, as well as of the dependent variables being tested (e.g., the effectiveness of imagery practice). This screening or pre-selection of participants on imagery ability scores may be more suitable for healthy samples than for clinical ones, however, due to the practical constraints of working with the latter groups. Methodologically, a potentially fruitful new direction for interdisciplinary research concerns the prospect of combining subjective and objective measures of motor imagery into a composite index. A first step in this direction has been taken by Collet, Guillot, Lebon, MacIntyre, and Moran (2011). We have developed a theoretical rationale for, and preliminary calculations of, a 'motor imagery index' (MII) based on data obtained from psychometric tools, qualitative methods, chronometric measures, and psychophysiological instruments. Although early results

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on the use of the MII are encouraging, further research is required to validate this new index.

To conclude, research on motor imagery processes can serve as a bridge between cognitive neuroscience and sport psychology. Specifically, imagery researchers in the former discipline can benefit from the insights into imagery perspective and the validation of imagery instructions offered by their counterparts in sport psychology. Similarly, imagery researchers in the latter discipline can benefit from cognitive neuroscientists' understanding of the theoretical mechanisms underlying motor imagery processes.

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