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# The role of working memory in sport

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The concept of working memory has received a great deal of attention in the last couple of decades and discussions of working memory are now common in almost all branches of psychology, including cognitive, clinical, social, developmental, and educational settings. Therefore, it is surprising that the concept of working memory has received a lot less attention in the field of sport psychology compared to other branches of psychology, especially since research in sport psychology has increasingly incorporated cognitive concepts such as attention, perception and decision-making, which are purported to rely heavily on working memory. Thus, it is essential, in our opinion, to systematically investigate the working memory system in the field of sports, which offers a fruitful domain to explore the validity of models developed in other fields. This review provides an overview of working memory theory and discusses its relevance in sport psychology. We end the review by giving an outlook of potentially fruitful research areas on working memory in sport.

**Keywords:** working memory; attention; sport; individual differences

## Introduction

Imagine the following scenario: the score is 49–50 in a little league basketball game with 15 seconds to play when the coach of the losing team calls a timeout to discuss the last offensive play. The instruction he gives to his playmaker is something like this: 'I want you to pass the ball to Kevin, then cut to the basket using the block (John) positioned on the high post in order to release yourself from your defender, while Kevin passes the ball to Mike, from whom you receive the ball under the basket'. What do you think the chances are of these instructions actually resulting in the successful execution of the intended play by a seven-year-old basketball player? Probably not too high! According to Cowan (2005), the feeling of being overwhelmed by new information is due to the limitations of a special type of memory that is commonly referred to as working memory (WM).

Controversy exists about the nature of WM (Miyake & Shah, 1999). Thus, we provide a brief historical overview of how the term came about, before we review and compare a subset of influential psychological models and theories of WM.

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### Historical overview

The distinction between a temporary primary memory store and a more durable secondary memory store was first made by William James (1890). This view was displaced in the mid-twentieth century by a single memory system view in which learning was thought to resemble the formation of associations, and forgetting was attributed to interference between competing associations (e.g. McGeoch & Irion, 1952). Hebb (1949) revived the two-component view by proposing a short-term memory (STM) and a long-term memory (LTM). STM was proposed to depend upon temporary electrical activity in the brain, while LTM was thought to be represented by more durable neurochemical changes. This view became the dominant view over the next decades as different independent groups of researchers (e.g. Brown, 1958; Peterson & Peterson, 1959) reported a rapid memory decay of small amounts of information after very brief recall intervals, if rehearsal was prevented. Moreover, Milner (1966) provided further evidence for at least two memory systems from his studies with neuropsychological patients.

The distinction between two or more kinds of memory was incorporated in a number of models of memory, of which the so-called modal model (Atkinson & Shiffrin, 1968) became the most influential. In this model, it was assumed that information flows from a parallel array of sensory memory to a single STM store. STM was considered an interface between LTM and sensory memory and was assumed to be responsible for both encoding information into LTM and retrieving information from LTM.

In the early 1970s, several problems emerged with the modal model. Critically, the model did not explain various behavioural data – e.g. that long-term learning depended on the elaboration of encoding and not the length of time spent encoding, as assumed by the modal model (Craik & Lockhart, 1972) – as well as neuropsychological evidence (e.g. Shallice & Warrington, 1970). Therefore, Baddeley and Hitch (1974) proposed a new model that fitted the existing data better than the Atkinson and Shiffrin (1968) model. For this reason, Baddeley and Hitch started their chapter on the multicomponent working memory system with the complaint: ‘Despite more than a decade of intensive research on STM, we still know virtually nothing about its role in normal human information processing’ (1974, p. 47).

## WM theory

It is usually Baddeley and Hitch (1974) who are associated with the concept of working memory, since they launched its empirical investigation, which continues today. In their famous chapter, Baddeley and Hitch (1974) highlighted a key theoretical construct – WM – which can be generally described as the cognitive mechanisms capable of retaining a small amount of information in an active state for use in ongoing tasks. This definition emphasizes that WM is essential for a whole range of behaviours and tasks. After the multicomponent model was first introduced in 1974, a vast amount of research has been conducted on WM, resulting in various theoretical conceptualizations. In this review we focus on psychological models that emphasize a close relationship between WM and attention, as we consider this link especially important in sport psychological research. We did not incorporate computational or biologically based models as this would go beyond the scope of this review (see Miyake and Shah (1999) for a review of these models). We end the section by outlining a consensual definition of WM as it is conceived today, in order to advance future research and theory development in the field of sport psychology.

### *Baddeley and Hitch's multicomponent model of working memory*

In the first attempt to empirically conceptualize their multicomponent model, Baddeley and Hitch (1974; revised by Baddeley (1986)) described WM as a limited cognitive resource that includes temporary, domain-specific storage buffers and a domain-general central executive system. The proposed WM comprised an attentional control system, the central executive, and two subsidiary slave systems, the phonological loop, which was assumed to be responsible for holding speech-based or acoustic information, and the visuospatial sketchpad, holding visual and spatial information (see Figure 1). The storage in both slave systems was assumed to fade within seconds unless the information was refreshed by rehearsal. The distinction between a verbal code and a visual code is fairly common in psychology and not unique to Baddeley's theory (cf. Paivio, 1971, 1986). An innovation in Baddeley's model is the idea of the central executive as an amodal control process. Baddeley and Hitch's method of choice for investigating their model was dual task studies, which offer empiricists the opportunity to show that complex behaviours, such as reasoning, involved coordinating storage and processing between the slave systems and the central executive. Specifically, findings from dual task studies suggest that only a limited amount of information can be held in the slave system while the executive works on new information (see Baddeley (2007) for a recent review).

Baddeley (2003) claims that the central executive is the most important, but least understood, component of WM. Thus, it was simply treated as a pool of general processing capacity in the original model (Baddeley & Hitch, 1974) responsible for all complex issues that could not be assigned to the two slave systems. The central

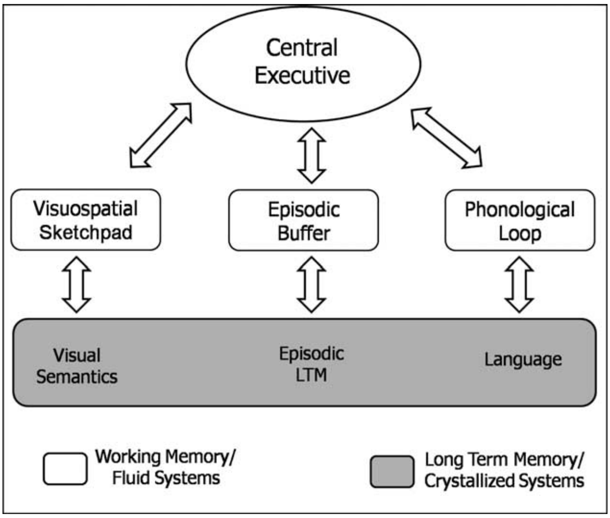

Figure 1. Baddeley's revised model of WM incorporating links with long-term memory (Baddeley, 2002, p. 93).

executive was treated as a convenient construct to address awkward questions, such as what determines when the sketchpad or the phonological loop is required, or how the information is combined. For this reason the central executive was frequently criticized as being conceptualized as a homunculus – sitting in the head – controlling cognition by pushing levers.

The first attempt to advance the concept came with the proposal (Baddeley, 1986) to adopt Norman and Shallice's (1986) model of attentional control as the central executive. This model assumes that behaviour is controlled at two levels. The first is fairly automatic and based on habits and schemas, whereby cues in the environment trigger the appropriate behavior – e.g., driving on one's daily route to work. The other level is a mechanism for overriding such habits and was termed the Supervisory Attentional System (SAS). The SAS is utilized when habit patterns are no longer adequate – e.g., if there is a construction site on one's daily route to work and one is forced to take appropriate action to circumvent it (Shallice, 1988; Shallice & Burgess, 1991).

After having provisionally accepted the SAS as the executive, Baddeley (1996) began to foster the conceptualization of the executive by postulating capacities that are needed by any attentional controller, namely the capacity to focus, to divide and to switch attention. The view of the central executive as an attentional control system differs from the initial concept that regarded the central executive as a limited capacity tool of general processing capacity, which could be used for a range of functions including both attentional control and temporary storage. According to Baddeley (2007), treating the central executive as a purely attentional system made it easier to frame fruitful questions and derive testable hypotheses. Having abandoned storage from the system, considerable problems were evident addressing the fourth proposed subcomponent of the executive – the interface between LTM and WM.

Although the first Baddeley and Hitch (1974) model was capable of accounting for a good deal of data, there appeared to be significant problems with the proposal that storage capacity was limited to the visuospatial and phonological subsystems. In general, these problems seem to suggest that the capacity of WM to store information exceeds that of the proposed subsystems. A further problem with the original model was integrating information from more than one source and the failure to address the concept of conscious awareness (Baddeley & Andrade, 2000). Moreover, observations from clinical samples and the frequently reported concept of chunking challenged the original model. In response to these problems, Baddeley (2000) put forth the concept of an episodic buffer as a fourth component of WM, which can be regarded as a fractionation of the initial central executive into an attentional control component (the executive described above) and an additional storage component.

### *The neural substrate of WM*

Recent research based on brain lesion patients and neuroimaging has focused on the anatomical localization of WM (see Henson, 2001; or Bledowski, Kaiser, & Rahm, 2010 for a recent review). The results of these studies fit the multicomponent model of WM fairly well (Baddeley, 2003). The phonological loop component is considered to be located in the left temporoparietal region (Vallar, DiBetta, & Silveri, 1997) with Broadmann area 40 as the locus of the storage component of the phonological loop and Broadmann area 44 being responsible for the rehearsal component of the loop (Paulesu, Frith, & Frackowiak, 1993). The visual-spatial component of WM is located primarily in the right hemisphere (Smith, Jonides, & Koeppe, 1996). Various studies have found evidence for a separation of areas involved in spatial and in visual or object coding (Levin, Warach, & Farah, 1985; Wilson, Scalaidhe, & Goldman-Rakic, 1993) – analogous to the *what* versus *where* distinction in visual processing (Mishkin, Ungerleider, & Macko, 1983). The neural substrate of the central executive is considered to be located in the frontal lobes (Henson, 2001; Smith & Jonides, 1997). The reviewed studies show that WM does not occupy a single anatomical location and therefore has to be considered a circuitry scattered over a large part of the cortex, recruiting a network of brain areas that are predominantly located in the prefrontal cortex and in parietal areas (Smith & Jonides, 1999).

### *WM as controlled/executive attention*

The controlled attention (e.g. Kane, Bleckley, Conway, & Engle, 2001) or executive attention[1] (Kane & Engle, 2002, 2003) theory of WM also regards WM as a multicomponent system (Baddeley & Hitch, 1974) responsible for active maintenance of information in the face of ongoing processing and/or distraction, but emphasizes the processing aspect of WM. Fundamental to the theory is that WM has a limited capacity constraining cognitive performance. All of the current conceptualizations of WM agree on the limited capacity of WM, whereas less agreement exists on the nature of the capacity limitations in WM (see Conway, Jarrold, Kane, Miyake, & Towse, 2007 for a review). For the purposes of the present review we favour theories that attribute capacity limitations to an attentional system. In contrast to the original notion of capacity as an amount of information (e.g., Miller, 1956) the controlled attention theory of WM states that working memory capacity (WMC) is a domain general measure, reflecting an individual's ability to control his/her attention (Conway et al., 2005). Guided by the controlled attention theory of WM, a large body of research has been conducted linking WM to higher order cognition. In this line of research, the so-called WM span measures emerged. These include the counting span, operation span, and reading span tasks, that are among the most widely used measurement tools in cognitive psychology today (Conway et al., 2005). WM span tasks typically present to-be-remembered target stimuli (e.g., digits or words) in combination with a demanding, secondary processing task such as comprehending sentences, verifying equations, or enumerating an array of shapes (Conway et al., 2005). In this respect, these tasks measure the ability of individuals to keep task-relevant information in a state of heightened activity during the execution of a processing task. Baddeley (2002) referred to research, which considers individual differences, as 'the most prominent feature in research on the topic [of WM] in North America' (p. 92). Importantly, individual differences do not refer to the WM concept as a whole, but rather to differences in functioning of the attentional component of WM, referred to as the central executive (Baddeley & Hitch, 1974), the supervisory attention system (SAS) (Norman & Shallice,1986) and executive control (Posner & DiGirolamo, 2000).

The main tenet of the controlled attention theory of WM is that WM span tasks predict complex cognitive behaviour such as reading comprehension (Daneman & Carpenter, 1980, 1983), language comprehension (King & Just, 1991; MacDonald, Just, & Carpenter, 1992), learning to spell (Ormrod & Cochran, 1988), following directions (Engle, Carullo, & Collins, 1991), vocabulary learning (Daneman & Green, 1986), writing (Benton, Kraft, Glover, & Plake, 1984), reasoning (Kyllonen & Christal, 1990), note-taking (Kiewra & Benton, 1988), bridge-playing (Clarkson-Smith & Hartley, 1990) and complex learning (Shute, 1991), because of the domain general controlled attention component shared by these tasks and the WM span tasks. Consistent with this view, a modification of the reading span task that requires mathematical processing instead of comprehending sentences is still an excellent predictor of language comprehension (e.g., Daneman & Merikle, 1996). By controlled or executive attention Kane and Engle (2002) describe an attention capability that holds memory representations (i.e., action plans, goals, or task-relevant stimuli) in a highly active state in the face of interference. For example, Conway, Cowan, and Bunting (2001) showed that individuals scoring high on WMC measures were better able to actively maintain relevant information and block out irrelevant information in a dichotic listening task. Participants had to 'shadow' words presented to one ear while ignoring a stream of words presented to the other ear. After a certain period of time the name of the participants was included in the ignored stream of words. The results showed that people with low WMC were significantly more likely to detect their name in the ignored channel, which the authors suggest is due to the fact that they could not focus their attention adequately on the required 'shadowing' task.

### *Cowan's embedded process model of working memory*

Cowan (2005) states that Baddeley's WM model has been the industry standard for many years since it is easy to grasp and explains many important phenomena. Nevertheless, Cowan (2005) thinks of Baddeley's model as not being exhaustive. In contrast to the multicomponent model of WM, Cowan emphasizes the function of WM – namely retaining relevant information into an unusually accessible state – and disregards the modalities. Cowan's (1995) embedded process model emphasizes a generic connotation of WM. The embedded process model distinguishes between three levels of activation: (i) elements in long-term memory that are inactive but with sufficiently pertinent retrieval cues; (ii) elements in long-term memory that are active above a certain level; and (iii) highly activated elements in the focus of attention. According to Cowan (1995), WM can be considered a complex construct involving all information accessed for a task. In contrast to Miller's (1956) 'magical number seven', Cowan (2001) regards the capacity limit of WM as being about four chunks in young adults.

### *Definition of WM*

The reviewed conceptualizations of WM share various commonalities and only differ in emphasis. Following a definition of Miyake and Shah (1999) based on a systematic review of 10 different models of WM (including the three conceptualizations outlined above), WM can be described in the following manner:

> WM is those mechanisms or processes that are involved in the control, regulation, and active maintenance of task-relevant information in the service of complex cognition,

> including novel as well as familiar, skilled tasks. It consists of a set of processes and mechanisms and is not a fixed ‘place’ or ‘box’ in the cognitive architecture. It is not a completely unitary system in the sense that it involves multiple representational codes and/or different subsystems. Its capacity limits reflect multiple factors and may even be an emergent property of the multiple processes and mechanisms involved. WM is closely linked to LTM [. . .]. (p. 450)

## WM in Sport psychology

Considering the importance of WM as a central cognitive mechanism, it is essential, in our opinion, to systematically investigate the WM system in the field of sports. According to Williams and Ericsson (2005), sport offers a fruitful domain to explore the validity of models developed in other fields, because the majority of sports require numerous higher-order cognitive abilities and are performed under conditions of extreme stress where the limits of human behaviour and achievement are being continually challenged and extended.

Conway et al. (2005) mention that discussions of WM are now common in almost all branches of psychology, including cognitive, clinical, social, developmental, and educational settings. Thus, WM plays an important role in contemporary global models of cognition (e.g. Anderson & Lebiere, 1998; Cowan, 1995), since it has proven to be involved in a wide range of complex cognitive behaviours, such as comprehension, reasoning, and problem-solving (Engle, 2002). Beyond this, WMC is an important individual-differences variable and accounts for a significant portion of variance in numerous general ability tasks (e.g. Conway, Kane, & Engle, 2003; Kane et al., 2004; Kyllonen & Christal, 1990; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002). Therefore, it is surprising that only a few attempts (reviewed below) have been undertaken exploring the role of WM in sporting contexts, especially since research in sport psychology has increasingly studied cognitive concepts such as attention, perception and decision-making, which are believed to rely heavily on WM (e.g., Knudsen, 2007). Of course not all behaviour relies on the WM system. Many daily actions (walking, driving, etc.) can be carried out fairly automatically with hardly any or no reliance on WM (e.g. Schneider & Shiffrin, 1977). This might be one reason why limited endeavours have been undertaken to systematically investigate the concept of WM in the field of sports, since a great deal of training in sports is undertaken in order to circumvent the limitations of WM and automize behaviours (Williams & Ericsson, 2005).

So far, we have described where the construct of WM came from, what it is, how it is conceptualized, and why it seems helpful for advancing research and theory development in the field of sport psychology. The next section considers the current and future role of WM in sport psychology research. First, we review existing literature on WM in sports before we suggest future research avenues that are derived from contemporary work emphasizing a close link between WM and attention (see Figure 2).

### *Review of existing research on WM in sport psychology*

#### *WM in motor learning and skill execution*

A common assumption within the skill acquisition literature is that the learner passes through different phases in the learning process placing different cognitive demands

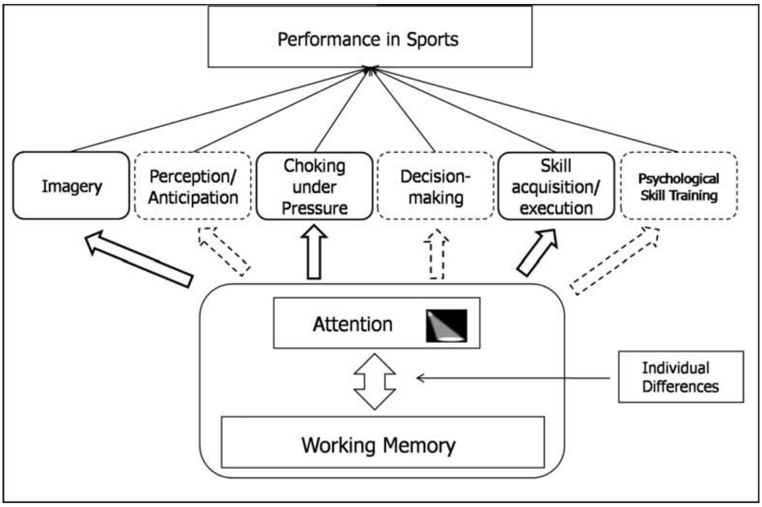

Figure 2. A framework relating isolated research areas in sport psychology to WM with attention as the central mediating mechanism. Dotted arrows and boxes represent hypothetical links that have to be established by future research.

on the learner. More specifically, it is assumed that during this progression, declarative knowledge is transformed into procedural knowledge (e.g. Anderson, 1982). Declarative knowledge is the kind of knowledge we can articulate and explain to others, whereas procedural knowledge is what we usually refer to as 'know-how'. Procedural knowledge is that kind of knowledge that controls our behaviour without us having to be consciously aware of it and which we are therefore often unable to describe (e.g. Maxwell, Masters, & Eves, 2003).

According to an early model of skill acquisition, Fitts and Posner (1967) state that learners proceed through three distinct learning phases that differ in their cognitive demands (see Figure 3). Fitts and Posner (1967) propose that during early stages of learning, motor skills are attended to in a step-by-step fashion and thereby require the application of declarative knowledge. The application of declarative knowledge has been shown to require the availability of WM, whereas procedural knowledge does not require WM (Berry & Broadbent, 1988). Thus, Fitts and Posner (1967) called this early phase the *cognitive phase*. After this stage, learners enter the *associative stage* in which WM involvement diminishes as learners begin to develop associations between specific stimuli and suitable action responses. The final stage is termed *autonomous stage* in which no or hardly any WM and thus attentional resources are required for the execution of the skill. The assumption that the cognitive demands decrease with continuous practice is common in the skill acquisition literature (e.g., Anderson, 1982; Schmidt, 1975; Schneider & Shiffrin, 1977) and not unique to Fitts and Posner (1967). Consequently, Anderson (1982) states that as skill level increases, information is restructured into a different type of skill representation, which is usually referred to as a procedure. Procedural knowledge does not require the same amount of attention and control as declarative knowledge which is involved in unpracticed skill execution. For this reason, a highly practiced soccer player would not need to attend to the execution of dribbling the

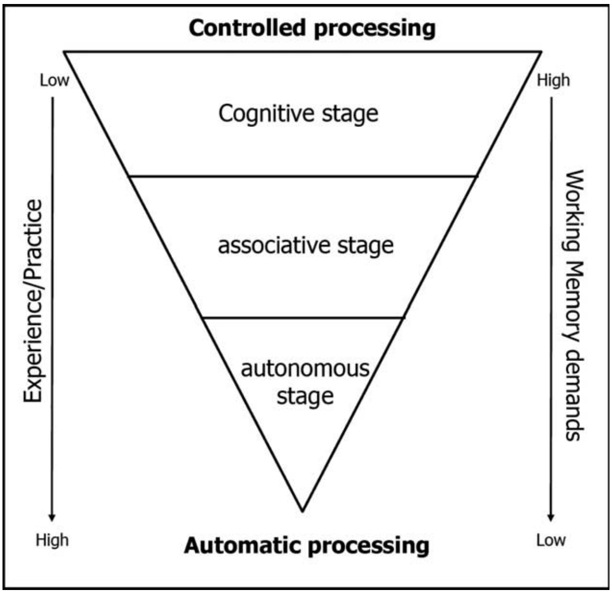

Figure 3. Fitts and Posner's (1967) model of skill acquisition as a function of the cognitive demands (WM) placed on the learner and his level of experience.

ball, which allows him to utilize his freed attentional resources for other aspects of the sport, such as scanning for open team-mates. Dual-tasking in sports, such as dribbling the ball and scanning for open team-mates, is only possible if one of the behaviours is proceduralized, because it would otherwise overwhelm limited capacity in WM.

Maxwell et al. (2003) state that stage theories in general give a too simple explanation in regards to the involvement of WM during motor skill learning and performance. In a series of experiments Maxwell and colleagues were able to show that processing of declarative knowledge is not characteristic of all early stages of learning and that skill acquisition does not have to progress from declarative to procedural knowledge. Implicit learning (e.g. Masters, 1992) is an example of how skills can be acquired without the progression from declarative to procedural knowledge by circumventing the contribution of WM during learning.

### *Implicit versus explicit learning*

Early work on implicit motor learning (Masters, 1992) has taken WM as an underlying construct into consideration. As discussed above, the early phases of skill acquisition place high cognitive demands on the learner that require WM. Research has shown that motor skills can be learned implicitly without early dependence on WM (see Masters and Maxwell (2004) for a review). Acquiring a skill implicitly and avoiding the accumulation of declarative knowledge can be advantageous compared to acquiring it explicitly – specifically it is thought to be more durable over time (Allen & Reber, 1980) and less prone to interference from psychological stress (Hardy, Mullen, & Jones, 1996; Masters, 1992). For this reason researchers have been interested in implicit learning and identifying methods that avoid the involvement of WM during learning (see Masters and Maxwell (2004) for a review). The methods utilized to circumvent or minimalize the contribution from WM during motor learning or motor output have included: (i) involving WM in alternative activities—e.g. random letter generation or articulatory suppression (MacMahon & Masters, 2002; Masters, 1992). Macmahon and Masters (2002) directly tested the effects of introducing both an articulatory suppression task (interfering with the phonological storage component of WM) and a random letter generation task (interfering with the central executive component of WM) on the accumulation of explicit rules while learning a golf putt. They could show that only the random letter generation task was sufficient to prevent the accretion of declarative knowledge. But since tasks involving the central executive are attention demanding, these tasks also disrupt performance on the primary learning task. Thus, future research attempts should try to find a secondary task that prevents explicit knowledge formation without interfering with motor learning; (ii) avoiding WM-dependent error correction and hypothesis testing (Maxwell, Masters, Kerr, & Weedon, 2001); (iii) occluding or diminishing external information that is processed in WM and in turn cannot be used to test hypotheses (Maxwell, Masters, & Eves, 2003); or (iv) presenting information to the learner that does not or hardly requires involvement of WM (Liao & Masters, 2001; Masters, Maxwell, & Eves, 2009).

According to Masters and Maxwell (2004), the reliance of a skill or task on WM can generally be measured in two ways. First, by verbal protocols, since the generation of verbalizable rules should only be possible when WM has been involved in skill acquisition, and second, by introducing a dual task, since this allows one to conclude if WM is utilized to perform the task by analyzing performance on both the primary and secondary task compared to the absence of a secondary task.

A common finding within the implicit learning literature is that motor skills learned implicitly, without early dependence on WM, are less prone to interference in pressure situations (e.g. Masters, 1992). The assumed explanation for this is that skill failures are often caused by a return to earlier modes of motor control under pressure. Evidence for this assumption is reviewed in the section below on ‘choking under pressure’.

### *Choking under pressure and WM*

One of the main concerns of sport psychological research is identifying the psychological variables that allow athletes or other performers to function at their best. For this reason, it is not surprising that a large body of research has emerged investigating performance in pressure situations (see Hill, Hanton, Matthews, and Fleming (2010) for a recent review) since performance pressure is a major component of almost every sport. Within this literature, the term ‘choking under pressure’ has emerged for describing situations in which individuals perform more poorly than expected given their skill level (Baumeister, 1984; Baumeister & Showers, 1986; Beilock & Carr, 2001). The concept of WM is frequently found in this body of literature when explaining the underlying mechanisms of pressure-induced performance decrements.

In order to understand the role of WM in performance pressure situations, we have to distinguish between sport skills that rely on WM, such as tactical decision-making, and skills that do not rely heavily on WM. The latter include automized sensorimotor skills, such as a golf putt or a basketball jump shot, since pressure influences these in a different manner. Let us first have a look at the theoretical assumptions about the effects of pressure on skills that rely on the WM system.

Baumeister (1984) claims that performance pressure results in anxiety, which in turn generates intrusive worries (Eysenck, 1985) about the situation and therefore occupies parts of the WM system (Ashcraft & Kirk, 2001; Hayes, Hirsch, & Mathews, 2008) which is purportedly needed for optimal performance. According to Schmader and Johns (2003), there is evidence suggesting that both stress and anxiety reduce the availability of WM, or more specifically WM capacity (Derakshan & Eysenck, 1998; Eysenck & Calvo, 1992). Various studies provide evidence for this theoretical assumption. For example, Schoofs, Preuß, and Wolf (2007) demonstrated WM impairments due to situational induced stress and Leach and Griffith (2008) provide evidence for restrictions in WM capacity during parachuting. Beyond this, Klein and Boals (2001) found that life event stress reduces WM capacity because people might engage some of their mental resources in order to suppress negative thoughts and feelings. These findings can be summarized as distraction theories since the pressure-induced worries cause something similar to a dual task situation with information needed for task performance competing with anxiety-related thoughts (Hill et al., 2010).

The cascade of pressure-induced performance decrements in well learned sensorimotor skills is assumed to occur differently. But again the concepts of WM and attention are of central importance. In order to understand the relationship between WM, attention and performance under pressure in well learned skills, such as a basketball jump shot, one needs to take the skill acquisition and automaticity literature into account (see the section above). Pressure has a different effect on these kinds of proceduralized skills as suggested by prominent *self-focus theories* (Baumeister, 1984), such as the *explicit monitoring hypothesis* (e.g., Beilock & Carr, 2001), or the *conscious processing hypothesis* (Hardy et al., 1996; Masters, 1992). Baumeister (1984) suggests that pressure raises self-consciousness about performing correctly. This self-consciousness causes performers to turn their attention inwards in order to avoid performance decrements by explicitly monitoring the skill execution. According to Duval and Wicklund (1972), this is due to the fact that attention focused internally inevitably generates a self-evaluation process that controls whether the current standard of performance matches the standard of performance one has as one's goal. Paradoxically, this has exactly the opposite effect than intended. Instead of avoiding performance decrements by investing attentional resources to skill execution, various studies (e.g. Baumeister, 1984; Beilock, Bertenthal, McCoy, & Carr, 2004; Gray, 2004) found evidence that this explicit attention disrupts well learned skills, because our conscious system is too slow to deal with the real time control of the proceduralized skills. In this respect, Masters (1992; or Masters and Maxwell (2008) for a recent review) proposed within *reinvestment theory* that the reinvestment of attentional resources to an automized skill results in dechunking of the movement as a whole into smaller independent units resembling a similar representation of the skill in early learning stages – a process that has elegantly been described as *paralysis by analysis* by the former world class tennis player Arthur Ashe.

Beilock (2007) called these two different mechanisms of choking under pressure 'pressure's double whammy', with the first mechanism interfering with WM-dependent skills by occupying limited capacity WM, and the second mechanism affecting well learned sensorimotor skills by causing a reinvestment of attentional resources to step-by-step skill execution.

A recent topic of interest that is highly related to the described mechanisms of choking under pressure in sport situations is the social psychological phenomenon of stereotype threat (Steele & Aronson, 1995) which suggests that merely introducing a negative stereotype about a social group can potentially result in performance decrements in members of that group. The underlying mechanisms are assumed to be similar to the ones described above (see Beilock and McConnell (2004) for a review). That is, either reducing available WM capacity due to worry about the negative stereotype (Schmader & Johns, 2003) or directing attention to the step-by-step movement control of well learned sensory motor skills (Beilock, Jellison, Rydell, McConnell, & Carr, 2006). Thus, Beilock and McConnell (2004) state that white basketball players, who are aware of the stereotype 'white men can't jump' might perform less well in a jumping task, whereas black basketball players who are aware of the stereotype that black athletes are not as athletically intelligent might perform less well in tasks involving tactical decision-making. Various studies in the field of sport have found evidence for this assumption in the sports of basketball (Stone, Perry, & Darley, 1997) and golf (Beilock et al., 2006; Stone, Lynch, Sjomeling, & Darley, 1999). Other potential sports in which negative or positive stereotypes might affect performance could be running (Baker & Horton, 2003), or table tennis and badminton considering the Asian dominance in these racket sports. Recently, Jordet (2009) published a study explaining the poor performance of English soccer players in penalty shootouts. Indeed, taking the findings on stereotype threat into account, it seems feasible that stereotype threat might be a further explanation for why English soccer players perform under their potential in important penalty shootouts.

### *Imagery and WM*

This section does not claim to be an exhaustive review of the existing imagery research in the sport psychological literature, but serves to highlight the importance of taking WM into account when discussing imagery as there seems to be a close link between WM and imagery (see the special issue of the *European Journal of Cognitive Psychology* entitled Imagery in WM and Mental Discovery) in sports as recently stated by Murphy, Nordin, and Cumming (2008).

According to Murphy et al. (2008), various theories have been discussed in the sport psychology literature explaining the workings of imagery, including the psychoneuromuscular theory (Jacobson, 1930; Richardson, 1967), the bioinformational theory of emotional imagery (Lang, 1979), the symbolic learning theory (Sackett, 1934), the triple-code theory (Ahsen, 1984), the dual-coding theory (Paivio, 1986), the action-language-imagination (ALI) model (Annett, 1988), and the arousal and attentional set theory (Feltz & Landers, 1983). Although all these theories have enhanced the theoretical understanding of imagery in sport settings, they only provide a vague or inadequate explanation of the underlying mechanisms of why and how imagery works. Furthermore, several applied models have been put forth, such as the PETTLEP (Physical, Environment, Task, Timing, Learning, Emotion, and

Perspective) (Holmes & Collins, 2001), the applied model of imagery use (Martin, Moritz, & Hall, 1999), and the Motor Imagery Integrative Model in Sport (Guillot & Collet, 2008), that have been useful for the application of imagery but also have their limitations in explaining how imagery can potentially influence behaviour.

For this reason Murphy et al. (2008) offer a theoretical framework including WM as a central component in order to strengthen the imagery behaviour link. Although the WM model has been mentioned frequently in combination with imagery in the cognitive psychology literature (Kosslyn, 1994; Paivio, 1986), it has only recently been incorporated in the sport psychological literature in Murphy et al.'s (2008) neurocognitive model of imagery in sport, exercise, and dance. Murphy and colleagues adopt Baddeley and Hitch's (1974) multicomponent WM system in their imagery model and state that WM plays a central role in understanding imagery. Furthermore, they stress that imagery cannot be fully comprehended without considering findings from the WM literature. The starting point of the neurocognitive model of imagery is the finding that imagery and perception share many commonalities and involve largely the same brain areas (Kosslyn, Thomson, & Alpert, 1997). Similar findings have been obtained regarding movement and imagery within the embodied cognition approach (see Beilock (2008) for a recent review in sport psychology). Future research is required to ascertain whether the model put forth by Murphy et al. (2008) can explain the workings of imagery better than the earlier models.

Applied sport psychologists have utilized and taught imagery – presumably a function of the visuospatial sketchpad – and self-talk strategies – presumably a function of the phonological loop – to numerous athletes for many years now (Anderson, 2000). Nevertheless, WM has only very recently found consideration in the sport psychological imagery literature (Murphy et al., 2008). This can be considered as one reason why unifying theories on how and why imagery works have been scarce or not very useful for deriving empirical hypotheses. Murphy et al.'s (2008) framework seems a great improvement in this respect, as it takes Baddeley's WM model into account, which has proven very useful for deriving testable hypotheses. To our knowledge, no sport psychological research has investigated WM as an underlying mechanism in imagery and self-talk, leaving the examination of such a relationship open to future research.

The reviewed sections on motor learning, choking under pressure, and imagery all highlight the importance of taking WM into consideration in the field of sport. In the next section we review recent research showing a close link between WM and attention and argue that this link might be highly important in advancing research and theory development on the topic of WM in sport psychology.

## ***Future research avenues on WM in sport psychology***

In the section on motor learning, we emphasized the distinction between automatic and controlled forms of processing. Numerous dual-process theories explicitly make this distinction and have become highly important for deriving testable hypotheses. These dual-process theories include: person perception (e.g., Gilbert, 1989; Zárate, Sanders, & Garza, 2000), stereotyping and prejudice (e.g., Devine, 1989), persuasion (e.g., Chaiken, 1980; Petty & Cacioppo, 1986), mental control (e.g., Wenzlaff & Wegner, 2000), self-regulation (Baumeister & Heatherton, 1996), emotion (Teasdale, 1999), and personality (Epstein, 1998). The main tenet of dual-process theories is that behaviour is determined by two qualitatively different modes of processing: automatic and controlled processing. In a nutshell, the commonality of dual-process theories is that they all share the idea that thoughts, behaviours, and feelings result from the interaction between bottom-up and top-down forms of attention (Feldman Barrett, Tugade, & Engle, 2004). Folk, Remington, and Wright (1994) emphasize this point neatly by describing the workings of attention in some way analogous to that of a thermostat. A thermostat is set to a specified temperature and then activates the heating system automatically when the temperature diverges from the pre-set temperature without requiring any further intervention from the person who set the thermostat. Thus, the person controls the thermostat, but the control is executed off-line. Folk et al. (1994) claim that the same is true for attention, by stating that cognitive goals determine attentional control settings in advance and that external stimuli that match the cognitive goals on some dimension will capture attention without any further cognitive involvement. The next section elaborates on this assumption by reviewing research that demonstrates that WM plays a decisive role in controlling attention.

### *WM and attention*

Scientists used to think of the relationship between memory and selective attention as operating only in one direction. Attention was conceptualized as a filter that selects only relevant information for access into the short-term processing stores (e.g., Atkinson & Schiffrin, 1968). Today, there is plenty of evidence showing that the contents of WM influence the guidance of selective attention (Awh, Jonides, & Reuter-Lorenz, 1998; Downing, 2000; Huang & Pashler, 2007; Soto, Heinke, Humphreys, & Blanco, 2005; Soto & Humphreys, 2007, 2008). Soto, Hodsoll, Rotshtein, and Humphreys (2008) argue that one reason for assuming a close link between WM and visual attention is that both seem to draw on a common pool of resources as indicated by a series of studies by Lavie (2005), who demonstrated that as the WM load increased, fewer resources seemed to be available to support efficient target selection and distractor rejection. For this reason, numerous researchers propose in large-scale theories of cognition that WM representations control the perceptual system via biasing the allocation of attention to objects that match features of the WM representations or are related to them (e.g., Anderson, Matessa, & Lebiere, 1997; Logan & Gordon, 2001).

A similar finding in line with this proposal is that words held in WM direct eye movements towards semantically related images (Huettig & Altmann, 2005). Of course, the properties of the external stimuli also play a role in determining the allocation of attention, as discussed before. An influential theory of attentional control that takes both bottom-up sensory factors and top-down WM factors into account is the *biased competition theory* (Desimone & Duncan, 1995) of selective attention. In a nutshell, the theory of Desimone and Duncan proposes that attention serves to enhance the response of behaviourally relevant neurons and that the effect of attention on neuronal responses is best understood as competition between competing stimuli and representations. For example, stronger sensory inputs usually have an advantage over weaker sensory stimuli, but the content of WM can bias the competition, tipping the balance towards the weaker stimuli. The winner of this competition then becomes the focus of attention.

Transferring the *biased competition theory* (Desimone & Duncan, 1995) of selective attention to the field of sport seems a promising approach for guiding future research, a point we demonstrate in the following example. A basketball point guard might not pass to the centre at the hoop who is waving (stronger stimulus) but instead passes to the shooting guard at the three-point line because he has silently been rehearsing, in the phonological loop component of his WM, the instructions he received from his coach during the last timeout, in which he was told that the team needs open three-point shots in order to win the game. In this manner, the *biased competition theory* seems applicable to a sport psychological context by proposing that stimuli such as a team-mate receive a competitive advantage when they match some kind of representation that is currently active in WM, thereby biasing selection in favour of one team-member and resolving the competition between the objects in the visual scene. 'The verbal content of the phonological loop readily triggers other responses, including both semantic associations and task relevant intentions' (Baddeley, 2007, p. 131). First results in our lab provide evidence for this relationship in sport settings. Specifically, we found that the content of WM plays a key role in biasing attention towards objects that are related to the contents held in WM in sport situations. In our experimental paradigm, we asked athletes to hold information in their WM, which is controlled for by a memory probe question, before they are asked to engage in a detection task or a tactical decision-making task. Our pattern of results suggested that search items that are related or close to items held in WM have a competitive advantage over items that are not related to the contents held in WM. Recent studies on inattentional blindness in sports (Furley, Memmert, & Heller, 2010; Memmert & Furley, 2007) might also be interpreted in this manner as results indicate that tactical decision-making declines when participants were required to not only name their tactical decision (performance task), but also identify the position of their direct opponent (monitoring task). The monitoring task participants had activated in WM directed their attentional focus to their direct opponent and therefore missed the pass to an open team-mate.

Based on the reviewed findings in this section, we think that the link between WM and attentional guidance can be considered a central mediating mechanism possibly reconciling isolated research areas in sport psychology. The present psychological research demonstrates that information currently activated in the circuitry of WM guides visual attention towards objects that are related to the information in WM (see Soto et al. (2008) for a recent review). Thus, it seems conceivable that this effect might generalize to a whole range of situations in sporting contexts. For example, one might argue that predictions from Attentional Control Theory (ACT) (Eysenck, Derakshan, Santos, & Calvo, 2007) are caused by the attentional guidance effects from WM. ACT assumes that anxiety leads to attention shifts attempting to detect the source of the threat causing the anxiety. In this respect one might argue that anxiety-induced worries held in WM direct the focus of attention towards threatening stimuli. Wilson, Wood, and Vine (2009) found evidence for ACT in the field of sport by demonstrating that anxious participants were more likely to focus on the 'threatening' goalkeeper in a football penalty kick compared to less anxious players. This is only one example of how the findings on the WM attention link might have the potential of reconciling isolated areas of research and help derive further testable hypotheses.

According to Cronbach (1957), a comprehensive account of human behaviour can only be achieved through the synergy of experimental and differential approaches to psychology.

> Individual differences have been an annoyance rather than a challenge to the experimenter. His goal is to control behaviour, and variation within treatments is proof that he has not succeeded. Individual variation is cast into that outer darkness known as 'error variance'. (Cronbach, 1957, p. 674)

Thus, more and more research takes individual differences into account. Individual differences in WM have shown to be predictive of a whole range of performance situations and therefore need to be taken into consideration as a moderating variable in sporting contexts.

### *Individual differences in WMC and their importance in sports*

Returning to the controlled attention theory of WM that states that there are individual differences in the ability to control attention that are predictive of a range of higher order cognitive tasks, it seems plausible that some athletes would benefit in their sports by having a greater WM capacity, enabling them to be more effective in controlling their attention. To our knowledge, no studies in the field of sport psychology have investigated individual differences in WMC among athletes.

As discussed earlier, controlled processing arises from the central executive aspect of WM and occurs when attention is applied in a goal-directed, top-down, or endogenous fashion. 'Without sufficient resources, controlled processing breaks down, and less appropriate or undesired responses emerge' (Feldmann Barrett et al., 2004, p. 556). Thus, coherent and goal-oriented behaviour in interference-rich conditions requires both the active maintenance of relevant information and the blocking or inhibition of irrelevant information. Previous research has shown that individuals that score high on WMC are better able to actively maintain relevant information and block out irrelevant information in a dichotic listening task (Conway et al., 2001).

A further prediction derived from the controlled attention theory of WM (Engle, 2002; Kane & Engle, 2003) states that high WMC subjects are better at acting according to a task goal instead of relying on habitual responses. Supporting evidence for this claim stems from correlations between WMC and simple attention task, such as the antisaccade task (Kane et al., 2001; Unsworth, Schrock, & Engle, 2004) or the Stroop task (Kane & Engle, 2003). In the antisaccade task, participants have to detect an abrupt-onset visual cue in the environment and use that cue to direct their attention and eyes to a spatial location that will subsequently contain a target. One condition in the antisaccade task demands major attentional control (antisaccade condition) in which the visual cue signals a location that does not contain the target in contrast to the other condition (prosaccade condition) in which the cue predictably appears in the same spatial location as the target. Thus, participants in the antisaccade condition must voluntarily move their eyes away from the cue towards the target or prevent their attention from being captured by the cue altogether. In the prosaccade condition, participants can allow their attention to be reflexively drawn towards the cue. Both conditions require the establishment of a goal-oriented task set, but only the antisaccade condition, in which the goal conflicts with habit, requires the maintenance of the goal in a highly active state for accurate responding by actively blocking or inhibiting the reflexive tendency of moving the eyes towards a cue. Kane et al. (2001) reported that high WMC subjects were significantly better in the antisaccade condition than low WMC subjects, whereas no differences were evident in the prosaccade condition. Similar findings were evident in the Stroop task (Kane & Engle, 2003), in which subjects are required to read out colour words, such as red, printed in different colours. These findings led to the general consensus (see Conway et al. (2007) for a review) that some of the WMC-related variation in the performance in attention tasks stems from individual differences in maintaining sufficient access to the current task goals instead of relying on reflexive habitual responding.

Following this line of argumentation, it seems highly fruitful to investigate individual differences among athletes in the ability of keeping task goals active instead of relying on a reflexive habitual response, since this ability might be of importance in tactical decision-making in various sports. For example, in team sports, some players might 'blindly' follow tactical instructions they received instead of flexibly adjusting their decision or action to the current situation. In conclusion, WMC differences should not affect a range of reflexive behaviours of athletes but should affect behaviour in situations of interference in which it is not sensible to rely on automatic routines. To our knowledge, no studies so far have investigated individual WMC differences among athletes in tactical decision-making.

A last topic of interest in sports regarding individual differences in WMC can be derived from recent research by Unsworth, Heitz, and Engle (2005) who provided first evidence that individual differences in WMC might further predict success at emotion regulation. As numerous situations from sporting events come to mind when performance declined due to the fact that athletes were no longer able to control their negative emotions, it seems highly interesting to investigate this relationship in competitive sports.

## Discussion and conclusion

When reviewing contemporary research in sport psychology, we frequently came across the term WM in isolated bodies of literature, such as skill acquisition, choking under pressure, and imagery. We argued that these topics could possibly be reconciled by recent findings showing that the contents of WM play a key role in biasing attention towards objects that are related to the contents held in WM and that this can be considered a central mediating mechanism. For example, one might argue that not only the momentary contents of WM control one's attentional focus, but that imagery could have a kind of training effect on a person's attentional focus by directing the focus of attention to task-relevant cues and away from irrelevant cues. This argumentation is not new and was first stated by Feltz and Landers (1983), who claimed that imagery could facilitate the development of a beneficial attentional set during sport performance.

Another area within sport psychology that might benefit from investigating the WM attention link is psychological skill training. Some of the positive effects of self-talk strategies, visuo-motor behaviour rehearsal, mental practice or goal-setting strategies might be attributable to loading WM with beneficial information which in turn helps control an athlete's attentional focus. The WM attention link intuitively seems to be a promising starting point in guiding future research in this area.

Finally, we made the claim that individual differences in WM capacity and more specifically in an individual's ability to control attention seem highly valuable for giving a comprehensive account of the role of WM in human behaviour in accordance with Cronbach's (1957) call for a unification of experimental and differential approaches to psychology. Instead of treating individual differences as error variance, sport psychological theory development could benefit from investigating individual differences in WM capacity as a moderating variable by indirectly illuminating the WM attention link as a central mechanism in explaining human behaviour in sporting contexts. Figure 2 summarizes this argumentation by showing how the WM attention link is central for understanding various sport psychological topics in consideration of individual differences. This framework might be useful for deriving empirical hypotheses and can be regarded as a first attempt at bringing together isolated research areas in sport psychology.

## Note

1. The terms executive attention and controlled attention are used synonymously at this point. Both of them are frequently utilized in the literature and usually refer to the same processes. The term executive attention emphasizes the family resemblance to other theories of executive function, executive control, and executive attention (e.g., Baddeley & Logie, 1999; Norman & Shallice, 1986; Posner & DiGirolamo, 2000), whereas the term controlled attention is more concrete and sizeable. Thus, the term controlled attention will be used in the following text.

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