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The relationship between working memory capacity and cortical activity during performance of a novel motor task

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ABSTRACT

Objectives: This study assessed whether individual differences in working memory capacity influenced verbal-analytical processes when performing a novel motor skill.
Design: Participants performed a tennis-hitting task in two conditions: no pressure and high-pressure.
Methods: Eighteen young adults participated in the study. EEG coherence between the T3-F3 and T4-F4 regions in the Beta1 and Alpha2 frequencies was recorded during performance in each condition. Verbal and visuo-spatial working memory capacity were assessed using the Automated Working Memory Assessment.
Results: No differences were found between the two conditions for hitting performance and EEG activity. However, across both conditions, verbal and visuo-spatial working memory were significant predictors of EEG coherence between the T3-F3 and T4-F4 regions in the Beta1 and Alpha2 frequencies. Larger verbal working memory capacity was associated with greater coherence while the opposite trend was observed for visuo-spatial working memory capacity.
Conclusions: These results indicate that larger verbal working memory capacity is associated with a greater tendency to use explicit processes during motor performance, whereas larger visuo-spatial working memory capacity is associated more with implicit processes. The findings are discussed with relevance to the theory of implicit motor learning.

The process of consciously updating movement patterns on the basis of performance outcome requires working memory involvement (Maxwell, Masters, & Eves, 2003). Information about previous performances must be held actively in (working) memory so that it can be used to adjust subsequent movement strategies. Thus, working memory can be considered to be involved when a person is consciously engaged in motor performance.

Working memory is limited by its capacity to hold information and this capacity differs for everyone (Daneman & Carpenter, 1980). Indeed, individual differences in working memory capacity (WMC) consistently reflect differences in conscious control mechanisms, namely attention control. For example, high WMC individuals outperform low WMC individuals in tasks that require the restraint of attention, such as antisaccade tasks (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Redick, Spillers, & Brewer, 2012; Unsworth, Schrock, & Engle, 2004) and Stroop tasks (Kane & Engle, 2003; Long & Prat, 2002; Unsworth et al., 2012). Similarly, high WMC individuals perform better in tasks that demand the constraint of attention in the presence of distracting information, such as flanker tasks (Heitz & Engle, 2007; Redick & Engle, 2006; Unsworth et al., 2012). As such, we argue that individual differences in WMC may also reflect differences in the ability to control attention during motor performance, thereby influencing the propensity to be consciously engaged in motor performance.

A series of studies by Anguera and colleagues highlighted the significance of WMC during motor performance with specific reference to visuo-motor adaptations (Anguera et al., 2012; Anguera, Reuter-Lorenz, Willingham, & Seidler, 2010, 2011). In these studies, greater (spatial) WMC was linked with faster learning

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during the early stages of practice. The authors theorized that motor error information is loaded into working memory and this enables the appropriate adaptations to transpire on subsequent trials. Working memory capacity was also recently found to be positively associated with score on the Movement Specific Reinvestment Scale (Buszard, Farrow, Zhu, & Masters, 2013) – a validated questionnaire that measures a person's likelihood to consciously control movements (Masters & Maxwell, 2008). Notably, this was observed for both children and adults. In the same study, WMC predicted change in performance during a “high-pressure” condition, with lower WMC individuals displaying greater improvements than higher WMC individuals. The high-pressure condition was designed to raise anxiety and therefore deplete working memory resources. Consequently, we concluded that individuals with high WMC were more affected by the depletion of their working memory resources, presumably because this diminished their ability to consciously control their movement patterns. This phenomenon has also been demonstrated in the performance of mathematical tasks in pressure situations (Beilock & DeCaro, 2007).

An important aspect of the Buszard et al. (2013) study was that WMC was measured using two tasks: (a) the counting recall task, which targets the verbal domain of working memory, and (b) the spatial recall task, which targets the visuo-spatial domain. Although recent evidence suggests that measures of WMC represent the same domain-general construct (i.e., attention control; Kane et al., 2004), Buszard et al. (2013) found that only scores on the counting recall task were associated with the propensity to consciously control movements. This implies that the verbal domain of working memory is implicated in the conscious control of motor performance; however, further investigation is required to support this conclusion. Indeed, in the present study, we included two measures of WMC that targeted the verbal and visuo-spatial domains respectively. We expected that the verbal measure of WMC would be associated with conscious processing during motor performance, but not the visuo-spatial measure.

Measuring conscious involvement during motor performance is a challenge for researchers. Typically, researchers have assumed that participants are relying on conscious processing if their performance declines under dual-task conditions or in a stressful environment, and if participants can verbally recall information regarding the step-by-step mechanics of the performance (e.g., Hardy, Mullen, & Jones, 1996; Lam, Maxwell, & Masters, 2009, Masters, 1992; Maxwell et al., 2003). Recently, however, methodology has advanced via the inclusion of neuroscientific approaches, namely electroencephalography (EEG) recordings. EEG measures the cortical activation in specific regions of the cerebral cortex for a given frequency, thereby allowing investigation of which neural networks are associated with conscious control mechanisms. The general consensus is that conscious processing during motor performance is characterized by greater cortical activity in the left hemisphere of the cortex, whereas greater activity in the right hemisphere is thought to represent superior visuo-spatial mapping of movements (e.g., Wolf et al., 2015). Specifically, a person is theorized to be consciously engaged in motor performance when there is less alpha power in the left temporal region – the area understood to be responsible for verbal-analytical processes and language (Cohen, 1993; Haufler, Spalding, Santa Maria, & Hatfield, 2000; Kerick et al., 2001; Springer & Deutsch, 1998).

The measurement of EEG coherence has further advanced the investigation of conscious processing mechanisms. “Coherence” measures the degree of connectivity between respective regions, with high coherence indicating communication between particular regions and low coherence inferring regional autonomy or independence (Nunez, 1995; Silverstein, 1995; Weiss & Mueller, 2003). Lower coherence between the left temporal and motor planning regions has been attributed to the attenuation of verbal-analytical communication with the premotor areas of the cortex and is indicative of expert performance (Deeny, Hillman, Janelle, & Hatfield, 2003; Wolf et al., 2015). Furthermore, lower coherence between these regions was observed in participants with low scores on the Movement Specific Reinvestment Scale (Zhu, Poolton, Wilson, Maxwell, & Masters, 2011). Thus, high coherence between the left temporal and motor planning regions is seemingly associated with the conscious control of motor performance via the engagement of verbal-analytical processes.

The present study utilized EEG coherence measurement as an indicator of conscious involvement during motor performance by specifically assessing the engagement of verbal-analytical processes. Additionally, participants were also required to perform a motor skill in a pressured environment, as pressure situations can often lead to increased attention to movement execution (i.e., conscious control), potentially disrupting skill mechanics (Baumeister, 1984; Gucciardi & Dimmock, 2008; Kinrade, Jackson, & Ashford, 2010; Masters, 1992; Masters & Maxwell, 2008). Moreover, increased anxiety due to perceived pressure is accompanied by increases in cortical activity, particularly between the left temporal and premotor regions (Chen et al., 2005; Hatfield, Haufler, & Contreras-Vidal, 2009; Hatfield et al., 2013; Zhu, Poolton, Wilson, Maxwell et al., 2011) and this is inversely related to performance outcome (Chen et al., 2005). As such, we expected that participants attempting to control their movements by increasing verbal-analytical thoughts would display poorer performance under pressure and this would be represented by an increase in EEG coherence between the left temporal and premotor regions.

The aim of this study was therefore to examine the relationship between WMC, EEG coherence and performance under pressure. Specifically, we intended to identify whether different measures of WMC that target the verbal and visuo-spatial domains respectively have unique relationships with EEG coherence between the temporal (left and right hemispheres) and premotor regions. We predicted that scores on the verbal measure of WMC would be positively associated with coherence between the left temporal and premotor regions (T3-F3) when participants performed a novel motor skill. This would imply that larger WMC in the verbal domain enables more verbal-analytical processing during the planning of movements, which presumably facilitates conscious processing during motor performance. In contrast, we expected to find no relationship between visuo-spatial WMC and EEG coherence between these regions. We also hypothesized that verbal WMC would be negatively associated with performance under pressure and that this would be associated with greater coherence between T3-F3. Once again, we did not expect to find a relationship between visuo-spatial WMC and performance under pressure. However, we did speculate that visuo-spatial WMC would be positively associated with EEG coherence between the regions theorized to be responsible for visuo-spatial motor planning (i.e., the right temporal and premotor regions: T4-F4).

1. Materials and methods

1.1. Participants

Eighteen young adults (7 males and 11 females) aged between 19 and 24 years ($M = 21.2$ years, $SD = 1.4$) participated in the study. All participants reported limited experience of playing recreational tennis (zero to 2 h throughout their life) with none ever having received professional coaching. Written voluntary consent was provided by all participants. The study was approved by the Human Research Ethics Committee of the University where the work was conducted.