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

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The relationship between working memory capacity and cortical activity during performance of a novel motor task
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 with implicit processes. The findings are discussed with relevance to the theory of implicit motor learning.

**KEYWORDS:** Cognitive Processes; Electrophysiology; EEG Coherence; Implicit Learning; Learning & Memory; Individual Differences.
The relationship between working memory capacity and cortical activity during performance of a novel motor task

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 & Pratt, 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 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 (see also Buszard, Farrow, Reid, & Masters, 2014). 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 & Deutch, 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).

Materials and methods

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 hours 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.

Experimental Design

First, participants’ WMC was measured using a well established WM assessment. Second, participants performed a tennis task in two conditions (no pressure, pressure) whilst wearing an EEG monitor (see Figure 1 for an overview of the montage between the motor task, the EEG monitoring system, and the working memory assessments). The task required
participants to hit a tennis ball with a tennis racquet towards a target on the ground. The number of shots that hit the target was recorded for each condition.

*** Insert Figure 1 about here ***

**Working Memory Assessment**

Working memory capacity was assessed using the Pearson Automated Working Memory Assessment (AWMA: Alloway, 2007). Two memory measures were extracted from the assessment; *counting recall*, which measured verbal working memory capacity, and *spatial recall*, which measured visuo-spatial working memory capacity. For *counting recall*, participants were presented with a series of shapes and were required to count aloud the number of red circles that appeared in each set of shapes. Afterwards, they had to recall the number of red circles in each set of shapes in the correct sequence. For *spatial recall*, participants viewed two shapes and were required to determine whether the shape on the right was the same or opposite to (i.e., a mirror-image of) the shape on the left. The shape on the right also featured a red dot and the participants had to remember the position of the dot(s) at the end of the trial. The AWMA program computed scores for each test. The test-retest reliability has been reported previously (Alloway, 2007), with moderate-to-high correlation coefficients found for each assessment ($r = .79$ to $.89$).

**Hitting Task**

Participants performed a tennis-hitting task in which the aim was to hit the ball over a 3m high net so that it landed on a 1m x 1m target located 9m away. The net was positioned 7m from the participant’s hitting location. All participants used a 19-inch Wilson tennis racquet and Wilson low compression balls (25% compression of a standard tennis ball). Participants performed the hitting task without any prior knowledge of what was
expected of them (i.e., they did not see another participant complete the task prior to performing). The researcher did not give a demonstration of how the task was to be performed. Participants were instructed that they could hit the ball in any way that they preferred (e.g., forehand, backhand, over arm, underarm), but they had to strike the ball before it bounced. Hitting performance was measured by counting the number of shots that landed on the target. The hitting task was performed in an unpressured condition (10 attempts to land the ball on the target) followed by a pressured condition (a further 10 attempts after a brief rest period of 5 minutes).

**Pressure Manipulation.** In the pressured condition, participants were informed that each attempt that landed on the target would prompt a payment of HKD50, up to a maximum of HKD200, but each attempt that missed the target would prompt a deduction of HKD50. Counterbalancing was not used because it was felt that participants would display little or no motivation during the unpressured condition if previously their performance had been linked to a financial reward. An anxiety thermometer (Houtman & Bakker, 1989) was used to examine the amount of anxiety that participants experienced before each condition.

**EEG Activity**

Throughout hitting performance, EEG was recorded from 14 scalp locations (AF3, F7, F3, FC5, T3, P7, O1, O2, P8, T4, FC6, F4, F8, AF4) in accordance with the standard international 10-20 system (Jasper, 1958) using a wireless EEG headset (Emotiv Technology Inc., USA), and then stored (bandpass filter, 0.2-45 Hz; notch filter, 50 Hz; sample rate, 128 Hz) on a notebook for offline processing and analysis. The validity of this EEG system has been demonstrated previously (Badcock et al., 2013; Debener, Minow, Emkes, Gandras, & de Vos, 2012). The time window for analysis was throughout the hitting task (10 attempts to land the ball on the target), which began when the researcher said “start” and finished when
the tenth ball landed on the ground. This approach has been utilized in similar experiments investigating complex motor skills (Baumeister, Reinecke, Cordes, Lerch, & Weiß, 2010; Baumeister, Reinecke, Liesen, & Weiss, 2008; Reinecke et al., 2011). Prior to each recording, the impedance at each location was checked to ensure an appropriate signal-to-noise ratio (i.e., contact quality). During the offline signal processing, EEG artifacts caused by eye blinks was removed by independent component analysis (ICA, Delorme & Makeig, 2004). In addition, an experienced EEG technician visually inspected the recordings and removed potential biologic artifacts (e.g., muscle activation or glosso-kinetic artifacts). Artifacts were distinguished from cortical activity according to the duration, morphology, and rate of firing. A Hamming window (128 sample and 50% overlap) was applied to the data in preparation for coherence analysis.

Coherence was defined as $|C_{xy}|^2$ of the EEG signals at electrode sites $x$ and $y$, where:

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}$$

and where $P_{xx}$ and $P_{yy}$ represent the power spectral density of $x$ and $y$, respectively, and $P_{xy}$ represents the cross power spectral density of $x$ and $y$. Coherence is a function of frequency with values between 0 and 1 indicating how well $x$ corresponds to $y$ at each frequency.

EEG T3–F3 and T4–F4 coherence were calculated in 1-Hz frequency bins and averaged across the appropriate frequencies to obtain the coherence values for Alpha2 (10–12 Hz) and Beta1 (13-20 Hz) frequency bandwidths (e.g., Deeny et al., 2003). The frequency bandwidths alpha2 (10–12 Hz) and beta1 (13-20 Hz) were selected as they are more likely to reflect global cortico-cortical communication sensitive to the frontal and temporal regions, whereas coherence in higher frequency bandwidths is sensitive to more localized activation of the cortex (Nunez, 1995; Von Stein & Sarnthein, 2000). All coherence estimates were
subjected to Fisher’s z transformation prior to analysis to ensure normal distribution. The processing and analysis steps described above were implemented with the EEGLAB toolbox (Delorme & Makeig, 2004) and custom scripts in MATLAB (MathWorks, USA).

**Statistical Analysis**

Paired t-tests were used to determine whether differences existed between the two conditions in EEG coherence and hitting performance. The standardised mean differences were reported using Cohen’s $d$. Pearson’s product moment correlation coefficients were used to assess the associations between verbal working memory capacity, visuo-spatial working memory capacity, hitting performance and the four EEG measures within the two conditions. Additionally, stepwise linear regression analyses were used to determine if any of the variables (verbal working memory capacity, visuo-spatial working memory capacity, and hitting performance) were predictors of T3-F3 and T4-F4 coherence in the two conditions. Variables were only entered into the regression analysis if the probability of $F < 0.05$.

Regression diagnostics, including DFFITS, Cook’s $d$ and DFBETAS, were calculated to check for influential observations.

**Results**

**Descriptive statistics**

With the significance level adjusted to 0.01 using the Bonferroni method, the difference in hitting performance between the no pressure condition ($M = 1.3$, $SD = 1.3$) and the pressured condition ($M = 2.2$, $SD = 1.6$) was not significant [$t (17) = -2.20$, $p = .04$, $d = .52$]. Similarly, EEG coherence in the Beta1 and Alpha2 frequencies in T3-F3 and T4-F4 regions was not significantly different in the two conditions either [Beta1 T3-F3, $t (17) = 0.53$, $p = .64$, $d = .12$; Alpha2 T3-F3, $t (17) = 0.48$, $p = .61$, $d = .12$; Beta1 T4-F4, $t (17) = -1.27$, $p = .66$, $d = .32$; Alpha2 T4-F4, $t (17) = 0.44$, $p = .66$, $d = .10$]. These results may have been due to the relatively small difference in self-reported anxiety scores between the two
conditions (unpressured, $M = 3.6, SD = 2.4$; pressured, $M = 4.6, SD = 2.4$, $[t(17) = -2.58, p = .02, d = .61]$. The mean score for the counting recall test (verbal WMC) was 30.1 ($SD = 5.3$), while the mean score for the spatial recall test (visuo-spatial WMC) was 33.4 ($SD = 5.0$).

**Correlation Coefficients**

The correlation coefficients among verbal WMC, visuo-spatial WMC, hitting performance, and the four EEG coherence measures, are presented in Table 1 (no pressure condition) and Table 2 (pressure condition). Of interest were the significant correlations between verbal WMC and EEG coherence between T3-F3 in both the Beta1 and Alpha2 frequencies in the pressure condition. Significant correlations were also found between coherence in these regions and visuo-spatial WMC in the no pressure condition. Visuo-spatial WMC was also significantly correlated with EEG coherence between Beta1 T4-F4 in the pressure condition.

*** Insert Tables 1 and 2 about here ***

**Stepwise Regression Analyses**

**Predicting EEG coherence during Condition 1 (no pressure).** When predicting Beta1 T3-F3 coherence, visuo-spatial WMC was entered into a stepwise linear regression first [$F(1, 17) = 6.32, p = 0.02$], which accounted for 28% of the variance in coherence (see Figure 2). Verbal WMC was entered second, [$F(1, 17) = 10.49, p = 0.001$] and these two variables accounted for 58% of the variance. Similarly, when predicting Alpha2 T3-F3 coherence, visuo-spatial WMC was entered into the equation [$F(1, 17) = 6.46, p = 0.02$] accounting for 29% of the variance. Given that visuo-spatial WMC was negatively correlated with all EEG measures, the results show that larger visuo-spatial WMC was associated with
less coherence between T3-F3. Comparatively, larger verbal WMC was associated with greater coherence in the T3-F3 regions.

With regards to Beta1 T4-F4 coherence, none of the predictor variables were entered into the equation; thus, none were found to be significant predictors of the variance in Beta1 T4-F4. However, for Alpha2 T4-F4, visuo-spatial WMC was entered into the regression analysis \([F(1, 17) = 5.06, p = 0.04]\) and accounted for 24% of the variance. Thus, larger visuo-spatial WMC was associated with less coherence between T4-F4. Hitting performance was not a significant predictor of T3-F3 or T4-F4 coherence for Beta1 or Alpha2 in this condition.

**Predicting EEG coherence during Condition 2 (pressure).** For predicting Beta1 T3-F3 coherence, verbal WMC was the first predictor entered into the regression analysis \([F(1, 17) = 5.16, p = 0.04]\), and accounted for 24% of the variance (see Figure 3). Visuo-spatial WMC was entered second \([F(1, 17) = 6.11, p = 0.01]\) and these two combined accounted for 44% of the variance. Verbal WMC was also a significant predictor of Alpha2 T3-F3 coherence \([F(1, 17) = 5.15, p = 0.03]\), accounting for 26% of the variance.

When predicting Beta1 T4-F4 coherence, visuo-spatial WMC was entered into the equation \([F(1, 17) = 5.05, p = 0.04]\) and accounted for 24% of the variance. None of the predictor variables were entered into the equation when predicting Alpha2 T4-F4 coherence. Similar to the first condition, hitting performance was not a significant predictor of T3-F3 or T4-F4 coherence for Beta1 or Alpha2 in the pressured condition.

*** Insert Figures 2 and 3 about here ***

**Discussion**
This study examined the relationship between WMC and EEG coherence when performing a novel motor skill. We were specifically interested in whether the verbal domain or the visuo-spatial domain of working memory had unique relationships with EEG coherence between the T3/T4 and F3/F4 electrode locations. These electrode locations are thought to represent activity between the left temporal and premotor regions, which has previously been associated with verbal-analytical processes during motor performance. We first hypothesised that verbal WMC (as measured by the counting recall task) would be positively associated with EEG coherence between T3-F3. Indeed, the results corroborated our hypothesis, implying that the verbal domain of WMC is associated with verbal-analytical processes during motor performance. The positive relationship suggests that individuals with larger verbal WMC were more likely to engage verbal-analytical processes when performing a novel motor skill.

Interestingly, approximately 50% of the variance in Beta1 T3-F3 coherence in each condition (44% and 58% for the two conditions) was explained by both verbal WMC and visuo-spatial WMC (as measured by the spatial recall task). This was somewhat surprising, as we did not expect visuo-spatial WMC to be associated with EEG activity at the electrode location T3. Furthermore, the relationship between visuo-spatial WMC and T3-F3 was negative in both conditions, as opposed to the positive relationship between verbal WMC and T3-F3 coherence. Hence, a clear distinction between verbal and visuo-spatial WMC was found. Whilst larger verbal WMC corresponded with greater verbal involvement during motor planning (as predicted), larger visuo-spatial WMC appeared to reduce the tendency for verbal involvement.

The significance of this finding is apparent when we consider theories of skill acquisition. Acquiring a motor skill with minimal reliance on verbal-analytical processes is referred to as implicit motor learning (Masters, 1992; Masters & Poolton, 2012) and can lead
to a number of benefits for the learner, including consistent performance in environments that are highly stressful or in situations that require multi-tasking (e.g., Hardy et al., 1996; Liao & Masters, 2001; Masters, 1992; Maxwell et al., 2003). Importantly, skills acquired implicitly are performed with lower EEG coherence between the left temporal and premotor regions (Zhu, Poolton, Wilson, Maxwell et al., 2011), which is theorized to facilitate neural efficiency (Kerick et al., 2001; Zhu, Poolton, Wilson, Hu, Maxwell, & Masters, 2011). Accordingly, our results suggest that larger visuo-spatial WMC may encourage a more implicit mode of learning, whereas larger verbal WMC may heighten the tendency for explicit monitoring of movements (Zhu, Poolton, Wilson, Maxwell et al., 2011). This viewpoint is consonant with a recent study that associated visuo-spatial WMC with performance improvements on an implicit sequence-learning task (Bo, Jennett, & Seidler, 2011). A function of the visuo-spatial system may therefore be to facilitate implicit motor learning. Notably, although we speculated that visuo-spatial WMC would be positively associated with EEG coherence between T4-F4 (i.e., the right temporal and premotor regions), only a weak relationship was observed. This infers that visuo-spatial WMC has a greater influence on suppressing verbal-analytical processing during motor performance than activating visuo-spatial mapping processes (T4-F4).

Our second hypothesis was that verbal WMC would be associated with poorer performance under pressure and this would be mediated by higher EEG coherence between T3-F3. However, we found no change in EEG coherence in the pressure condition, nor did performance decline. In fact, the mean performance score across all participants improved (albeit not significantly) in the pressure condition. It appears that the monetary incentives used to create pressure did not induce sufficient anxiety in the participants, as evidenced by the self-reported anxiety scores. Manipulating the environment to manufacture pressure is a challenge for researchers, with behavioural changes in performance sometimes difficult to
eliciting in ‘laboratory’ pressure conditions (see Cooke et al., 2014). For instance, Zhu, Poolton, Wilson, Maxwell et al. (2011) attempted to induce pressure by detailing a cover story to the participants delivered by the leading professor of the study. Whilst EEG alpha coherence increased, there was no accompanying decline in performance. Even Hatfield et al. (2013) found no change in performance outcome despite an increase in cortical activity during a pressured condition that seemingly heightened anxiety. It appears that small changes to neural processes do not always equate to noticeable changes in performance (Landau, Schumacher, Garavan, Druzgal, & D’Esposito, 2004).

Although this study advances our understanding of the relationship between WMC and conscious processing mechanisms via the measurement of EEG coherence, the results should be interpreted in light of the methodological limitations. First, we must be careful drawing conclusions from correlation data, especially in a study with a small sample size (n = 18). Second, because the participants were all university students, the range of WMC in this study was limited and we acknowledge that we did not assess participants with pathologically “low” WMC. Presumably, the relationship between WMC and verbal-analytical processes would not be linear if we examined a large cohort of participants with a greater range of WMC scores. Working memory has limited capacity and, therefore, it is more reasonable to assume that the relationship will follow a non-linear algorithm (e.g., a log₂(χ) relationship). Third, we must always take care when interpreting EEG data. For instance, how do we know that the brain regions activate the same processes for every person, especially given that individual differences in WMC may be mediated by differences in the neural functioning (Kane & Engle, 2002)? Indeed, like previous EEG studies investigating motor performance, we acknowledge that due to volume conduction we cannot be certain that cortical activity at the electrode location T3 is representative of the left temporal region and consequently verbal-analytical processing. It is possible that the activity recorded for each electrode may
have actually been caused by activity in nearby areas. Nonetheless, we are confident in the validity of our data given that the results are consistent with a growing body of research utilizing the same approach.

In summary, the present study adds to the WMC literature by increasing our knowledge of the link between WMC and motor performance. Specifically, the study highlights the unique differences between the verbal and visuo-spatial domains of working memory and provides insight into how they influence conscious processing during motor performance. Larger verbal WMC was associated with a greater coherence between T3-F3 regions, which has previously been associated with verbal-analytical processes when performing movement skills, while larger visuo-spatial WMC corresponded with a decrease in T3-F3 coherence. These findings raise interesting questions with respect to whether larger verbal WMC promotes explicit motor learning or whether larger visuo-spatial WMC encourages implicit motor learning.

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References


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**Figure Captions**

*Figure 1.* The montage of the three elements of the study: (a) the motor task, (b) the EEG monitoring and (c) the working memory tasks.

*Figure 2.* The relationship between verbal WMC and EEG coherence between the T3-F3 regions, and visuo-spatial WMC and EEG coherence between the T3-F3 regions (no pressure condition). *represents that the x variable was a significant predictor of the y variable in the regression analysis. DFFITS ranged between -.06 and .12, Cook’s $D$ ranged between 0 and .96, and DFBETAS ranged between -.17 and .16. These values were not considered to be influential (Cook & Weisberg, 1982; Cousineau & Chartier, 2010).

*Figure 3.* The relationship between verbal WMC and EEG coherence between the T3-F3 regions, and visuo-spatial WMC and EEG coherence between the T3-F3 regions (pressure condition). *represents that the x variable was a significant predictor of the y variable in the regression analysis. DFFITS ranged between -.07 and .09, Cook’s $D$ ranged between 0 and .93, and DFBETAS ranged between -.09 and .22. These values were not considered to be influential (Cook & Weisberg, 1982; Cousineau & Chartier, 2010).
Figure 1.
Figure 2.
Figure 3.
Table 1

*Correlation Coefficients during Condition 1 (no pressure)*

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<td>5. Alpha2 T3-F3</td>
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<td>.80**</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6. Beta1 T3-F3</td>
<td>-.06</td>
<td>-.23</td>
<td>.05</td>
<td>.10</td>
<td>.25</td>
<td>-</td>
</tr>
<tr>
<td>7. Alpha2 T4-F4</td>
<td>-.17</td>
<td>-.17</td>
<td>.09</td>
<td>.03</td>
<td>.03</td>
<td>.78**</td>
</tr>
</tbody>
</table>

** Correlation is significant at the $p = 0.01$ level (2-tailed); * Correlation is significant at the $p = 0.05$ level (2-tailed).

Table 2.

*Correlation Coefficients during Condition 2 (pressure)*

<table>
<thead>
<tr>
<th></th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Verbal WMC -</td>
<td></td>
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<tr>
<td>2. Visuo-spatial WMC</td>
<td>.18</td>
<td>-</td>
<td></td>
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<tr>
<td>3. Hitting performance</td>
<td>.08</td>
<td>.45</td>
<td>-</td>
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<tr>
<td>4. Beta1 T3-F3</td>
<td>.49*</td>
<td>-.36</td>
<td>-.19</td>
<td>-</td>
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<tr>
<td>5. Alpha2 T3-F3</td>
<td>.51*</td>
<td>-.28</td>
<td>-.13</td>
<td>.86**</td>
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</tr>
<tr>
<td>6. Beta1 T4-F4</td>
<td>-.17</td>
<td>-.49*</td>
<td>-.38</td>
<td>.06</td>
<td>.10</td>
<td>-</td>
</tr>
<tr>
<td>7. Alpha2 T4-F4</td>
<td>-.27</td>
<td>-.43</td>
<td>-.37</td>
<td>-.15</td>
<td>-.03</td>
<td>.89**</td>
</tr>
</tbody>
</table>

** Correlation is significant at the $p = 0.01$ level (2-tailed); * Correlation is significant at the $p = 0.05$ level (2-tailed).
The relationship between working memory capacity and cortical activity during performance of a novel motor task

Tim Buszard, Damian Farrow, Frank Z. Zhu & Rich S. W. Masters

Highlights
- Examined EEG coherence in the Beta1 and Alpha2 frequencies during motor performance
- Larger verbal WMC was associated with greater T3-F3 coherence
- Verbal working memory was therefore linked with explicit processes
- Larger visuo-spatial WMC was associated with reduced T3-F3 coherence
- Visuo-spatial working memory was theorized to facilitate implicit processes