The association of sport modes with visuo-spatial cognition in athletes: An ERP study

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Abstract

The aim of this study was to investigate the relationship between sport modes and visuo-spatial cognition among young athletes. Forty-eight young adults, including 16 open-skilled athletes, 16 close-skilled athletes, and 16 non-athlete controls, were recruited. Visuo-spatial cognition was measured by a non-delayed and delayed matching-to-sample paradigm outside a sports-related context, including attention and working memory (WM) conditions, where behavioral indices and P3 components were recorded. The results demonstrated that regardless of training modality, the athlete groups exhibited shorter reaction times in both the visuo-spatial attention and WM conditions than the control group. Similarly, larger P3 amplitudes were observed in both athlete groups than in the control group in the WM condition. These findings suggest that regardless of sport training experiences, athletes may have better fundamental cognition at the behavioral and neurophysiological levels.

Key words: expertise; sports; cognitive function; event-related potential

Introduction

A growing body of evidence has shown that exercise positively affects cognitive function (Hillman, Erickson, & Kramer, 2008), particularly executive function, a top-down process that is involved in goal-directed behavior and comprises subcomponents such as inhibition, working memory (WM), and cognitive flexibility (Diamond, 2013). A cross-sectional study indicated that older adults with higher levels of physical activity (PA) exhibited superior working memory compared with those with lower levels of PA (Chang, Huang, Chen, & Hung, 2013). In addition, longitudinal studies have indicated that chronic exercise is associated with the facilitation of inhibition among older adults (Chuang, Hung, Huang, Chang, & Hung, 2015) and children (Chang, Tsai, Chen, & Hung, 2013).

Athletes have superior sport performance and physical fitness due to prolonged engagement in training. In a meta-analysis, Mann, Williams, Ward and Janelle (2007) showed that athletes performed better than non-athletes in cognitive tasks in sports-related contexts. Furthermore, Voss, Kramer, Basak, Prakash and Roberts (2010) suggested that expertise might be transferred from sports-related cognitive tasks to general cognitive function. In line with this statement, recent studies have found that athletes, particularly interactive athletes (e.g., fencers, soccer players, volleyball players, table tennis players), perform better than non-athletes in executive control paradigms outside of sports-related contexts (Alves et al., 2013; Taddei, Bultrini, Spinelli, & Di Russo, 2012; Verburgh, Scherder, van Lange, & Oosterlaan, 2014; Wang, Guo, & Zhou, 2016).

Notably, Voss et al. (2010) indicated that the sport training mode may moderate the sport-cognition relationship, and interceptive sports showed largest effects, followed by strategic sports and static sports. Schmidt and Wrisberg (2008) suggested that sports can be categorized into two modes, open skilled and close skilled, depending on the variability, predictability, and complexity of the performance environment. Comparing to close-skilled sports (e.g., jogging, swimming, cycling), open-skilled sports (e.g., racket sports, team sports) theoretically require a greater investment of cognitive resource during execution given the constantly changing and unpredictable environment. An animal study showed that wheel running with high cognitive demands stimulated neurogenesis in the dentate gyrus more than wheel running alone (Fabel et al., 2009). Human studies have also supported the cognitive benefits of exercises with high cognitive demands (Lustig, Shah, Seidler, & Reuter-Lorenz, 2009; Tranter & Koutstaal, 2008). For example, Wang et al. (2013) indicated that athletes in open-skilled sports (i.e., tennis players) demonstrated better inhibition than those in close-skilled sports (i.e., swimmers). A similar result was found for problem solving (Jacobson & Matthaeus, 2014). Altogether, these findings suggest that open-skilled sports could produce larger cognitive benefits than close-skilled sports (Voss et al., 2010).

Visuo-spatial cognition represents the ability to perceive and process complex spatial information. Notably, one study indicated that visuo-spatial cognition is more responsive to exercise training than verbal aspects (Shay & Roth, 1992). The majority of research has focused on the visuo-spatial cognition benefits of cardiovascular fitness (CRF) or training (e.g., running, cycling) and the facilitation of CRF. For example, Wang, Liang, et al. (2015) found that CRF was positively associated with better visuo-spatial attention-related neurocognitive performance among young adults (Wang, Liang, et al., 2015). Similar results were found during a visuo-spatial memory paradigm in preadolescent children (Chaddock et al., 2010) and older adults (Erickson et al., 2009). Studies have also indicated that CRF training (i.e., running) for six weeks and one year can enhance visuo-spatial memory among young (Stroth, Hille, Spitzer and Reinhardt (2009) and older adults (Erickson et al., 2011), respectively. Moreover, Niemann, Godde and Voelcker-Rehage (2014) found that while both CRF exercise and coordinative exercise training increased the volume of the hippocampus among older adults, coordinative exercise specifically increased the volume of the right hippocampus, a brain area that is associated with visuo-spatial processing. Furthermore, Wang, Tsai, et al. (2015) indicated that female badminton players exhibited superior visuo-spatial neurocognitive performances than non-athletes. A similar result was found among handball and soccer players (Heppe, Kohler, Fleddermann, & Zentgraf, 2016). These findings speculate that coordinative and/or open-skilled exercise training could produce similar or larger benefits for visuo-spatial cognition compared with CRF exercise training. Therefore, an examination for the relationship between sport modes and visuo-spatial cognition among athletes should be encouraged to broaden the current knowledge.

To investigate differences in cognitive performance as a function of sport modes, measures of neurophysiological correlates, such as event-related potential (ERP), can provide further insight. ERP offers excellent temporal resolution and provides a finer evaluation of distinct cognitive operations, such as stimulus encoding or response preparation (Luck, Woodman, & Vogel, 2000). The amplitude and latency of the P3(b) component represents the amount of attention resources being allocated to task-relevant stimuli and the stimuli classification speed, respectively (Kutas, McCarthy, & Donchin, 1977; Polich, 2007). It has been suggested that P3 measures are associated with different aspects of cognitive processing (Polich, 2007), including visuo-spatial attention and WM (Müller & Knight, 2002). P3 measures have been employed to study the association of exercise with cognition. For example, Wang and Tsai (2016) showed that individuals with higher levels of PA exhibited larger P3 amplitudes during a visuo-spatial paradigm compared with those with lower levels. Similarly, Taddei et al. (2012) found that fencers demonstrated larger P3 amplitudes than non-athletes during a Go/No-go paradigm. Furthermore, Tsai and Wang (2015) found that individuals who regularly participated in open-skilled exercise exhibited larger P3 amplitudes than those who participated in close-skilled exercise during a task-switch paradigm. Altogether, these findings highlight the sensitivity of P3(b) to examine the effects of exercise on cognition.

Overall, the aim of current study was to examine differences in visuo-spatial cognition performance between athletes who engaged in different sports training using both behavioral and ERP (i.e., P3) measures. We hypothesized that both athlete groups (i.e., open-skilled and close-skilled) would exhibit better visuo-spatial cognition than the control group. In addition, we predicted that the sport mode would modulate cognitive performance, with open-skilled athletes exhibiting superior behavioral and neuro-electrical performance compared with close-skilled athletes.

Methods

Participants

Forty-eight collegiate participants (mean age = 20.60 ± 1.71 years) were recruited from universities [redacted] Participants were further assigned to the open-skilled sports group (OS; n = 16, 7 women, 1 left-handed) if they were badminton or table tennis players, the close-skilled group (CS; n = 16, 7 women, 1 left-handed) if they were swimming, triathlon, and track and field (e.g., mid-distance running) athletes, or the control group (Con; n = 16, 7 women, 1 left-handed) if they had no experience in sports training or regular participation in exercise. Participants in the OS and CS groups had experience competing at the division 1 level for an average of 10 years, and they had consistently attended intensive sports training for an average of 10 hours per week in the 6 months preceding their participation in the experiment. All participants met the following criteria: They (a) were non-smokers; (b) had normal or corrected-to-normal vision; (c) were without diagnosed psychiatric or neurological disorders; (d) did not take medication that would influence central nervous system functioning; and (e) were able to perform physical exercise without discomfort or health risks based on an assessment with the Physical Activity Readiness Questionnaire (PAR-Q). All participants signed the written informed consent approved by the Research Ethics Committee of [redacted]

Procedures

Participants were instructed to visit the laboratory for two testing sessions. All sessions were completed within one month and separated by at least one week. Participants were required to refrain from food and drink consumption, except water, 1.5 hours before each session. In the first session, participants first completed the demographic questionnaire, socio-economic status of the family (SES) (Hollingshead & Redlich, 1958), handedness inventory (Oldfield, 1971), PAR-Q, International Physical Activity Questionnaire (IPAQ) (Liou, Jwo, Yao, Chiang, & Huang, 2008), and informed consent form. Then, participants were instructed to sit on a comfortable chair and were fitted with an electrode cap in a quiet and dimly lit data acquisition room. Afterwards, participants were provided cognitive task instructions and performed practice trials. The formal data recording was commenced when participants reached an accuracy rate of 80% in the practice trials. In the second session, participants were administered a non-verbal IQ test using Raven's Progressive Matrices: SPM Plus Sets (Styles, Raven, & Raven, 1998). Next, participants' height and weight were measured, and the CRF measurement was administered. Participants were given US $30 compensation right after they completed the second session.

Measures

Cardiovascular Fitness Assessment. We measured CRF by peak oxygen consumption (VO2 peak) for each participant utilizing the Bruce Treadmill Protocol, which is a maximal graded exercise test (GXT) on a motorized treadmill. During this protocol, both the speed and slope increased every 3 min until participants were exhausted, and the test was terminated when at least two of following three criteria had to met: (a) a plateau in VO2 with increasing exercise intensity; (b) a respiratory exchange ratio above 1.10; and (c) HRmax within 15 beats of age-predicted HRmax (220-age) (American College of Sports Medicine, 2006; Howley, Bassett, & Welch, 1995).

Cognitive Assessments. The present study employed a modified non-delayed and delayed matching-to-sample test similar to one used in a previous study (Wang & Tsai, 2016), which examined visuo-spatial attention and WM, respectively (see **Fig1**). The task was programmed with STIM 2.0 software (Neuroscan Ltd, El Paso, TX, USA). All stimuli were presented on a 17-inch computer monitor that was placed 60 cm in front of the participants. The stimuli consisted of a red dot (0.5^{o} x 0.5^{o}) randomly positioned within a 3.8^{o} x 7.4^{o} gray rectangle. The rectangle appeared either in the center of the screen or 5.9^{o} to the left or right of the central fixation point.

In the Attention condition (non-delayed), two rectangles were presented simultaneously; one rectangle was placed in the center of the screen, while the other was placed either to the left or to the right of the center. The dot could appear in any one of 9 locations (i.e., center, center right, center left, upper center, upper right corner, upper left corner, lower center, lower right corner, lower left corner) within its rectangle. The two rectangles were presented for 180 ms, a duration shorter than is typical for voluntary saccades, to minimize the potential effects of unwanted saccades on the results (Wang & Tsai, 2016). Participants were instructed to determine whether the location of the red dots appeared in the same position within their respective rectangles.

In the WM condition (delayed), the stimulus 1 (S1) was presented for 180 ms with an equal probability on either the left or right of the central fixation (0.5^{o} x 0.5^{o}), followed by a 3-second delay. Stimulus 2 (S2) then appeared for a duration of 500 ms in the center of the screen. Participants were instructed to retain the position of the S1 red dot in their memory during the 3-second delay and then determine whether its position was identical to the position of the red dot in S2.

Before testing began, participants were reminded that accuracy and speed were equally important. Participants pressed the “YES” button with their left thumb when the S1 and S2 red dots were in the same position within their respective rectangles, and they pressed the “NO” button with their right thumb when they were not. The response time windows were 2000 ms for both the attention and working memory test conditions.

After achieving the 80% response accuracy threshold on the practice trials, participants were administered 240 trials, each consisting of 4 blocks of 60 trials. Participants were provided feedback on each response (‘correct’, ‘incorrect’) immediately after the 2000 ms response period, during both the initial test trials, and during the 240 recorded trials. The order of equal numbers of attention condition trials and working memory condition trials were randomly presented within each block. Rest intervals between blocks were between 3 and 5 minutes.

Data on the response accuracy of all trials, the response times (RT) and the intra-individual variability in RT (ICV), which was measured by the SD/RT formula (Taddei et al., 2012), of the correct trials were used as performance indices. In addition, we computed the accuracy-adjusted RT using the mean RT/accuracy rate formula to avoid the potential influence of a speed-accuracy trade-off strategy on task performance (Sutherland & Crewther, 2010)

Electroencephalographic Recording. Electroencephalographic (EEG) activity was recorded with 30 electrode sites using an elastic electrode cap (Quick-Cap, Compumedics Neuroscan, Inc., Charlotte, NC, USA) according to the modified International 10-20 System. Electrooculographic (EOG) activity was measured using 4 electrodes placed at the outer canthus of each eye and above and below the left orbit. Scalp locations were referred to linked mastoid electrodes, while the ground electrode was attached to the mid-forehead on the Quick-Cap. All electrode impedances were below 5 kΩ. The EEG data acquisition was performed with a sampling rate of 1000 Hz, using a DC- to 200-Hz filter and a 60-Hz notch filter.

For data reduction, EOG activity was corrected using the algorithm described by (Semlitsch, Anderer, Schuster, & Presslich, 1986). Epochs were defined as 100 ms pre-stimulus to 1000 ms post-stimulus. The baseline was defined as the mean amplitude of the 100-ms pre-stimulus interval. The data were filtered using a 30-Hz low-pass cutoff (12 dB/octave), and ERP trials with an amplitude outside the range of ±100 μV were excluded. Only trials with correct responses were averaged. Peak detections were performed on midline electrode sites (i.e., Fz, Cz, Pz) from grand-averaged waveforms because the recordings for the P3 component are thought to be maximal and consistent with these electrode sites (Polich, 2007). An amplitude of P3 was defined as the maximal positive peak within a 300- to 600-ms post-stimulus window.

Statistical Analysis

Data analyses were performed using the SPSS 21.0 software system. A one-way ANOVA was separately computed to test the homogeneity of the demographic variables, IQ, physical activity, and CRF across groups. Three (Group) x 2 (Condition) ANOVAs were separately performed on behavioral data (i.e., RT, ICV, response accuracy, and accuracy-adjusted RT) to examine group differences in behavioral performance. Three (Group) x 2 (Condition) x 3 (Site: Fz, Cz, Pz) ANOVAs were performed on P3 amplitude and latency to examine the interactions of Group with Condition or Site in the ERP. Post-hoc comparisons were conducted using LSD significant difference tests. An alpha = .05 was set as the level of statistical significance for all analyses. Partial eta-squared effect sizes (η_p^2) were reported for significant effects or interactions.

Results

Demographic data

Table 1 presents participants' characteristics. There was no significant difference (p >.05) across groups in terms of age, sex, height, weight, hours playing video games per week in past years, and SES. The control group had a higher non-verbal IQ than the athlete groups ($F(2,45)= 11.70$, $p < .05$).

With regards to sport characteristics, there was no difference (p >.05) between the two athlete groups in terms of the number of years engaged in sport training. The close-skilled group had longer daily training hours within the past six months than the open-skilled group. ($t(16.659)= -2.63$, $p < .05$). Both athlete groups had greater higher-intensity physical activity levels (i.e., vigorous, moderate, and overall METs) than the control group ($p < .05$), but no significant difference was detected in lower-intensity physical activity levels (i.e., walking) across three groups (p >.05). A post hoc comparison demonstrated no significant difference in higher-intensity physical activity levels between the open- and close-skilled groups (p >.05) (i.e., vigorous, moderate, and overall METS). Furthermore, there were significant differences in CRF levels across the three groups. A post hoc comparison demonstrated that the close-skilled group had the highest cardiovascular fitness, followed by the open-skilled group and then the control group ($F(2,45)=11.10$, $p < .05$). However, there was only a marginal difference between the open-skilled and control groups ($p = .06$).

Behavioral data

Table 2 presents the results for response accuracy, RT, ICV, and accuracy-adjusted RT. The response accuracy revealed a condition effect (F(1,45)=93.398, p<.05, η_p^2=0.686), with a higher accuracy in the non-delayed condition (95.91%) than in the delayed condition (89.05%). Furthermore, the RT results revealed main effects of condition (F(1, 45)=9.739, p<.05, η_p^2 =0.178) and group (F(2,45)=5.198, p<.05, η_p^2=0.188), with shorter RT in the delayed condition (694.16 ms) than the non-delayed condition (727.07 ms). Both athlete groups exhibited shorter RT than the control group regardless of the condition, but there was no difference between sport modes (OS: 659.49 ms & CS: 692.59 ms < Con: 779.76 ms). The ICV results yielded a significant effect of condition (F(1,45)=50.379, p < .05, η_p^2=0.528), and the delayed condition (0.242) had a larger ICV than the non-delayed condition (0.198). Similar results were found for RT and accuracy-adjusted RT, with a significant effect of group (F(2,45)= 5.167, p < .05, η_p^2=0.187). A post hoc comparison indicated that both athlete groups had a shorter accuracy-adjusted RT than the control group regardless of condition, but there was no difference between the two athlete groups (OS: 7.14 $^{ms}/_{\%}$ & CS: 7.51 $^{ms}/_{\%}$ < Con: 8.46 $^{ms}/_{\%}$).

An additional analysis was performed on RT that included CRF as a covariate. The result was similar to the primary analysis, which showed main effects of group (F(2, 45)= 4.829, p <.05, η_p^2 = 0.18) (OS: 660.11 ms & CS: 687.02 ms < Con: 784.72 ms).

ERP Analysis

For P3 amplitude, there was significant main effect of electrode (F(1.414, 63.62)=117.724, p<.05, η_p^2=0.723) and an interaction of condition and group (F(2, 45)=3.453, p < .05, η_p^2=0.133). A post hoc comparison revealed that Pz (12.25 μV) had the largest amplitude, followed by Cz (7.45 μV) and Fz (3.59 μV). Furthermore, both athlete groups had a larger amplitude than the control group in the delayed condition (F(2,45)=4.701, p<.05, η_p^2=0.173) (OS: 8.17 μV & CS: 9.38 μV >Con: 5.24 μV), but there was no significant difference in the non-delayed condition (F(2,45)= 0.747, p =.480, η_p^2=0.032). There was no significant effect of condition (F(1,45)= 0.036, p =.851, η_p^2 =0.001) or interactions of group and electrode (F(4,90)=0.468, p=.759, η_p^2 =0.02), electrode and condition (F(1.593, 71.666)=1.615, p =.209, η_p^2 =0.035), or group, electrode and condition (F(4,90)=0.963, p =.432, η_p^2 = 0.041). The P3 waveform during the delayed condition is shown in **Figure 2**.

Regarding P3 latency, there was a main effect of electrode (F(2,45)=7.275, p < .05, η_p^2 =0.139). A post hoc comparison indicated that Fz (399.09 ms) and Pz (389.53 ms) latencies were shorter than Cz (406.77 ms). There were no significant effects of condition (F(1,45)=0.06, p =.808, η_p^2=0.001) or group (F(2,45)=0.152, p=.859, η_p^2=0.007) or interactions of group and electrode (F(4,90)=0.816, p=.518, η_p^2=0.035), condition and electrode (F(1.685,75.818)=2.27, p =.109, η_p^2=0.048), group and condition (F(2,45)= 0.632, p=.536, η_p^2 =0.027), or group, condition and electrode (F(4,90)=0.75, p =.561, η_p^2=0.032).

An additional analysis was performed on P3 amplitude, which included CRF as a covariate in the WM condition. The result was similar to the primary analysis, which showed main effects of group ($F(2, 45)= 3.629$, $p<.05$, $\eta_p^2 = 0.14$) (OS: 8.16 μV & CS: 9.52 μV > Con: 5.12 μV).

Discussion

The aim of current study was to investigate the relationship between sport modes and visuo-spatial cognition among young athletes using behavioral and neuro-electrical measures. The main findings are that regardless of their training modality, athletes exhibited a faster processing speed, as indexed by RT, than the control group for both visuo-spatial attention and WM. The faster processing speed among athletes could not have resulted from a speed-accuracy strategy because there was no group difference in response accuracy or accuracy-adjusted RT. Regarding ERP results, both athlete groups demonstrated a larger P3 amplitude in the WM condition than the control group. Our findings suggest that both open- and close-skilled sport training are associated with a faster processing speed during visuo-spatial cognition and better neural resource allocation during visuo-spatial WM.

The findings that the athletes presented better cognitive performance than the controls have advanced the current knowledge. As previous works have evidenced that exercise training facilitates cognitive performance among children (Chang, Tsai, et al., 2013), young adults (Stroth et al., 2009), and older adults (Chuang et al., 2015), the current study replicated previous findings. Moreover, it went one step further by showing that athletes exhibit superiority not only in sports-related contexts (Mann et al., 2007) but also in general cognitive domains (Alves et al., 2013; Jacobson & Matthaeus, 2014; Taddei et al., 2012; Verburgh et al., 2014; Wang et al., 2013). In particular, given that previous studies have examined the cognitive performance of athletes by focusing on executive function domains without high spatial demands, the present study contributes to the literature by employing a cognitive task with high spatial demands (Wang, Tsai, et al., 2015). Furthermore, the employment of a cognitive task with conditions that varied in processing complexity verified that athletes committed to prolonged open- and close-skilled sport training are associated with superior visuo-spatial processing at both the perceptual and imperative levels.

Regarding the neuro-electrical findings of P3 amplitude, the current study found that athletes invested greater neural resources for the evaluation/classification of imperative stimuli, as indexed by a larger P3 amplitude, during the retrieval phase of WM than the controls. These results support previous works focused on non-athletes, which suggests that exercise training could facilitate executive function, at least in part, via the modulation of neural resource allocation to task-relevant stimuli (Chang, Huang, et al., 2013; Chang, Tsai, et al., 2013). We also broaden the current knowledge by revealing the neurophysiological correlates of visuo-spatial WM associated with prolonged sport training irrespective of the training modalities.

On the other hand, previous studies have not measured CRF, which may bias the findings, when they explore the sport-cognition relationship among athletes (Taddei et al., 2012; Wang et al., 2016; Wang, Tsai, et al., 2015). The current study did not reveal a significant difference between the open-skilled athlete group and the control group. Correspondingly, this study extends the current knowledge by revealing that athletes, especially open-skilled ones, surpass non-athletes on visuo-spatial neurocognitive performance due to sport expertise rather than fitness.

Notably, the absence of a training effect on P3 amplitude during the visuo-spatial attention condition is worth further discussion. Previous studies have indicated that fencers demonstrated a larger P3 amplitude in No-go stimuli relative to non-athlete controls, whereas no group difference in P3 amplitude was observed for Go stimuli, during a Go/no go paradigm (Di Russo, Taddei, Apnile, & Spinelli, 2006; Taddei et al., 2012), which indicates that the training effects could be elicited on cognitive aspects with higher mental loads. In terms of visuo-spatial processing, a greater investment of cognitive resources is required for WM than for attention (Gazzaley & Nobre, 2012). These results, in concert with our findings, indicate that sport training-elicited benefits for neural resource allocation may be specific to cognitive domains with high mental loads (i.e., WM), not lower-order cognition with perceptual and discriminative demands (i.e., attention).

With respect to P3 latency, the current study found no significant group differences. This result was consistent with that of a previous study that utilized a Go/No-go paradigm (Taddei et al., 2012) and found no significant difference in P3 latency between athletes and controls, whereas a group difference was revealed in P3 amplitude. In addition, Wang and Tsai (2016) found that individuals with higher levels of physical activity exhibited a larger P3 amplitude than those with lower levels during visuo-spatial processing, but no group difference was found in P3 latency. Accordingly, we speculate that sport training enhances visuo-spatial WM through the modulation of neural resource allocation, not the speed of stimulus evaluation/classification.

Moreover, there was no difference between athlete groups in behavioral (i.e., RT) or neuro-electrical (i.e., P3 amplitude) measures after controlling CRF, which was inconsistent with our hypothesis. This discrepancy could be explained, at least in part, by two reasons. First, the dose-response relation between exercise training and cognitive performance should be considered when interpreting this result (Pesce, 2012; Voelcker-Rehage & Niemann, 2013). Specifically, the weekly training hours within the past six months were higher among the close-skilled athletes than the open-skilled athletes. The difference in the volume of training could, in turn, have affected the cognitive benefits such that the close-skilled athletes received greater cognitive benefits from training than their open-skilled counterparts. Another possible explanation is that most of the close-skilled athletes were recruited from a department of physical education, in which case they may have participated in different types of exercise, including open-skilled exercise, in addition to formal training. Accordingly, it is possible that the volume of sport training and recreational exercise participation played a critical role in biasing the association of training modalities with cognitive function in athletes, which should be carefully considered by future related studies.

Unlike previous studies (Wang & Tsai, 2016; Wang, Tsai, et al., 2015) that demonstrated that the WM (delayed) condition had a higher accuracy and a shorter RT than the attention (non-delayed) condition across groups in a non-delayed and delayed matching-to-sample task, the current study showed that the RT was shorter in the WM condition than the attention condition, which is inconsistent with the results of past studies. We also revealed that the WM condition exhibited higher ICV than the attention condition. As far as the authors are concerned, these results could be interpreted in relation to the higher unpredictability and complexity of the imperative stimulus during the WM paradigm, which resulted in higher uncertainty and impulsive responses, as indexed by greater intra-individual ICV and shorter RT.

There are several limitations of this study. First, its cross-sectional design prevents causal inferences. Second, the current study applied non-delayed and delayed matching-to-sample tasks that included visual-spatial attention and WM conditions, which omitted the examination of other high-order cognitions. Third, we recruited collegiate athletes, which may limit the generalizability of findings to athletes from difference ages (e.g., adolescents).

Conclusions

In conclusion, the current study demonstrated that regardless of training modes, athletes exhibited superior visuo-spatial cognitive performance relative to non-athletes at the behavioral level. Furthermore, the training-elicited benefits can be extended to neuro-electrical level of visuo-spatial WM processing. Our findings not only provide converging evidence that athletes' expertise can be transferred from sports-specific contexts to general cognitive contexts but also shed light on the association of training modality with visuo-spatial cognition at different cognitive levels.

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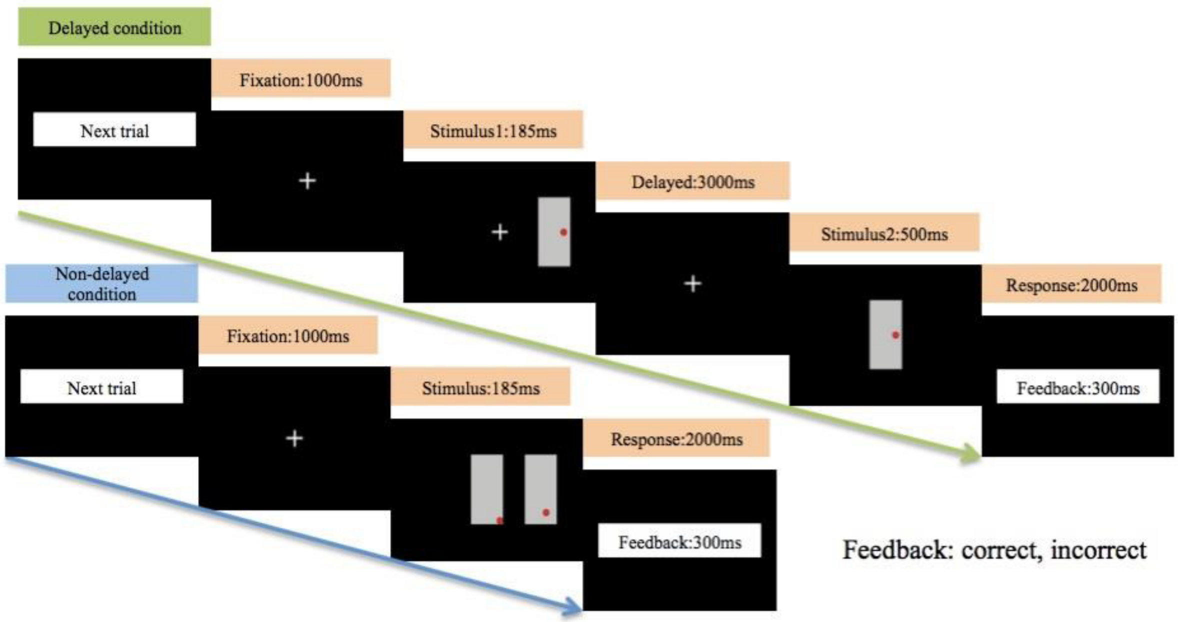

Figure 1. Illustration of the non-delay and delayed matching-to-sample task

Table 1 Descriptive data for participants' demographic and sport characteristics of each group

Variables	OS (n=16)	CS (n=16)	Con (n=16)	Total (n=48)
Woman	7	7	7	21/48
Left-hand dominant	1	1	1	3/48
Age (years)	19.9 (1.3)	21.2 (2.4)	20.7(1.1)	20.6 (1.7)
Height (cm)	170.2 (9.4)	170.7(6.7)	169.0 (9.1)	170.0 (8.3)
Weight (kg)	63.9 (11.8)	61.5 (10.0)	59.9 (11.7)	61.8 (11.1)
Non-verbal IQ test	38.3 (4.2) *	41.7 (5.1)	46.7 (5.4)	42.2 (5.9)
SES	2.1 (0.8)	2.5 (0.9)	1.9 (0.7)	2.2 (0.8)
Video game experience in past six months (week/hours)	6.3 (3.3)	6.9 (3.5)	10.9 (4.7)	8.5 (4.4)
Table tennis / badminton	9/7			10.9 (4.7)
Track-field / swimming / triathlon		7/8/1		
Training years	10.8 (2.2)	9.7 (3.2)	0	10.2 (2.8)
Daily training hours in past six months	8.7 (1.3) *	12.3 (5.3)	0	10.5 (4.2)
Vigorous PAL (METs)	5685.0 (1562.1) *	6615.0 (2183.8)	246.0 (312.0)	4182.0 (3223.3)
Moderate PAL (METs)	2287.5 (1348.8) *	1740.0 (1515.0)	533.9 (752.1)	1520.5 (1429.2)
Walk PAL (METs)	1103.6 (1423.4)	681.1 (586.8)	882.6 (674.3)	889.1 (965.4)
Total PAL (METs)	9076.1 (2257.5) *	9036.1 (3454.0)	1662.4 (1236.0)	6591.6 (4281.2)
CRF (ml/kg/min)	46.2 (7.2) *	55.8 (11.9)	39.6 (9.7)	47.2 (11.7)

Notes. 1. The number in parentheses is the standard deviation; 2.* = group effect; 3. PAL= physical activity level; 4.METs=metabolic equivalents.

Table 2 Behavioral Performance Results of Each Group

Condition	Dependent Variables	OS (n=16)	CS (n=16)	Con (n=16)
Delayed	Accuracy (%)	88.99 (3.99)[b]	88.79 (4.98)	89.38 (4.56)
	RT (ms)	637.07 (82.54)[ab]	670.94 (145.02)	774.47 (153.19)
	Accuracy-adjusted RT (ms/%)	7.19 (1.14) [a]	7.57 (1.66)	8.69 (1.86)
	ICV (SD/RT)	0.246 (0.05)[b]	0.243 (0.0478)	0.239 (0.0457)
Non-delayed	Accuracy (%)	96.27 (2.28)	95.99 (3.91)	95.47 (3.94)
	RT (ms)	681.91 (62.32)[a]	714.24 (111.15)	785.06 (108.37)
	Accuracy-adjusted RT (ms/%)	7.10 (0.68) [a]	7.45 (1.14)	8.22 (1.03)
	ICV (SD/RT)	0.19 (0.0325)	0.195 (0.0391)	0.209 (0.046)

Note. 1 The number in parentheses is the standard deviation; 2. [a] = group effect ; [b] = condition effect

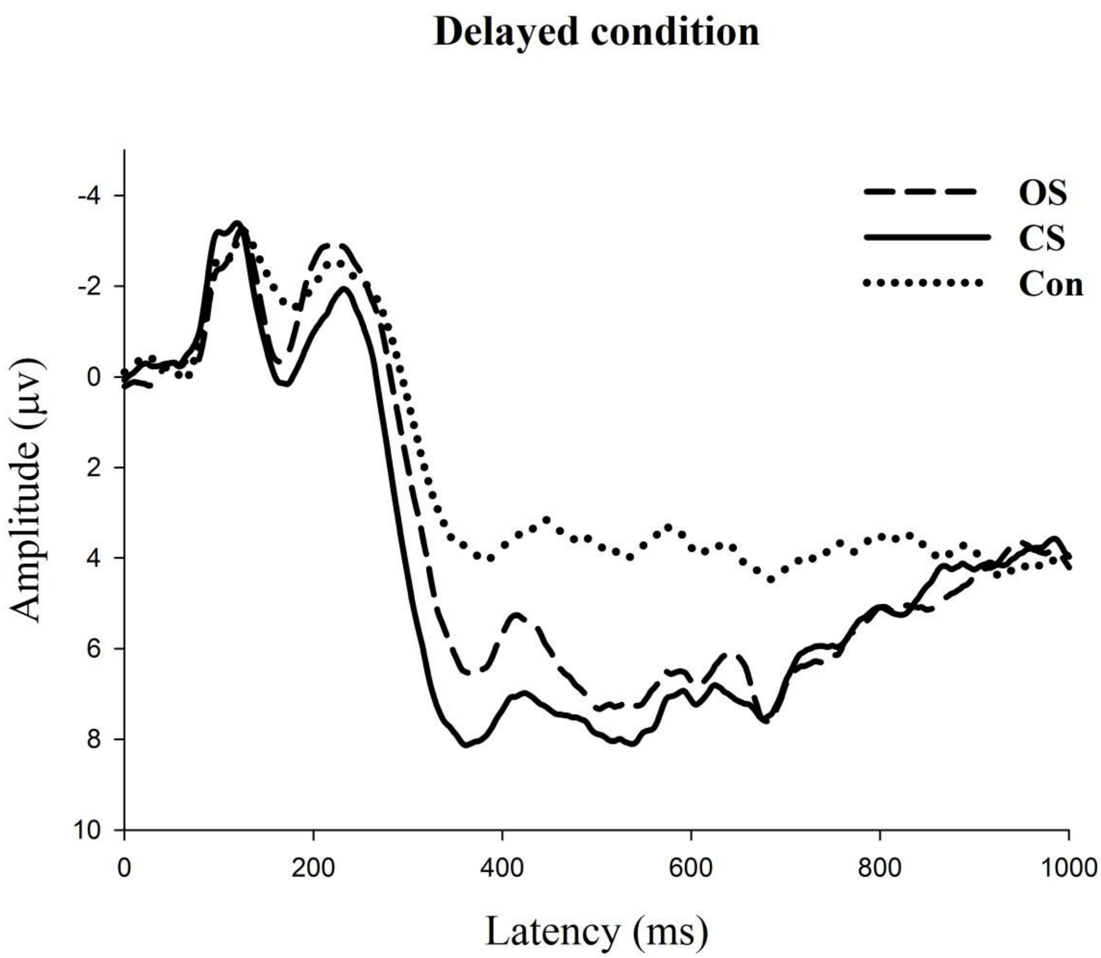

Figure 2. The grand average ERPs stratified by group and delayed condition

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