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Article

Cognitive Function of Climbers: An Exploratory Study of Working Memory and Climbing Performance

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Abstract

Sport climbing requires a combination of physical and cognitive skills, with working memory (WM) playing a crucial role in performance. This study aimed to investigate the association between WM capacity and climbing ability, while considering potential confounding factors including sex, age, education level, and climbing experience. Additionally, the study compared prefrontal cortex (PFC) hemodynamic responses among different climbing ability groups and sex during WM performance. Twenty-eight climbers participated, with WM assessed using the eCorsi task and PFC hemodynamic responses measured with near infrared spectroscopy (NIRS). Initial linear regression analyses revealed no association between WM and climbing ability. However, significant associations were found after adjustment for covariates. Specifically, sex (p = .014), sex in conjunction with age (p = .026), sex combined with climbing experience (p = .022), and sex along with education level (p = .038) were identified as significant predictors of differences in WM between Expert and Elite climbers. Additionally, notable differences in PFC hemodynamic responses were observed between Expert and Elite climbers, as well as between sexes during the WM task, providing support for differences in WM capacity. This study contributes to understanding the complex relationship between WM capacity and climbing performance, emphasizing the need to account for influencing factors in assessments.

Keywords: brain activity; climbing; executive function; forward working memory; embedded processes model of working memory

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Sport climbing is a sport that requires a combination of physical and cognitive skills (Fryer et al., 2017; Garrido-Palomino et al., 2020). Among the cognitive functions that has garnered attention in the context of sport climbing, working memory (WM) has emerged as a crucial factor (Heilmann, 2021; Whitaker et al., 2019). In essence, WM involves the active retention of pertinent information for brief periods, facilitating cognitive processes like planning and reasoning, which are useful in guiding behavior (Baddeley, 2012). WM is characterized by limited capacity, typically encompassing around 3 to 5 information chunks, although this capacity can vary among individuals (Cowan, 2010). According to the embedded-processes model (Cowan, 2010), the efficiency of WM hinges on attentional control and its interaction with information from both short- and long-term memory, which acts as a guide for selecting and loading data into WM.

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Researchers have used the dual task paradigm to explore the functional role of WM in the planning and execution of motor skills among climbers (D'Esposito & Postle, 2015; Spiegel et al., 2013). This paradigm requires participants to simultaneously perform two cognitively demanding tasks, such as climbing while recalling a list of words. When both tasks compete for WM processing and storage demands, performance tends to be less efficient than when tasks are performed individually (Anderson et al., 2010). The decline in climbing performance during a dual-task (Green et al., 2014; Green & Helton, 2011) underscores the role of WM in managing information relevant for planning motor sequences. Additionally, beyond the evidence related to WM involvement in climbing (Green et al., 2014; Green & Helton, 2011), research conducted by Garrido-Palomino et al. (2020) highlights that higher-level climbers possess superior attentional control, which is especially beneficial for on-sight lead climbing. This suggests that enhanced attention significantly contributes to climbing performance, indicating its pivotal role alongside WM in the cognitive demands of climbing.

A common method for determining climbers WM capacity is the forward Corsi block task (Higo et al., 2014). In this task, participants observe a visual sequence of blocks and reproduce it in the same order as presented. This task is suitable for evaluating WM in the climbing context (Heilmann, 2021; Whitaker et al., 2019), given that climbers typically adhere to a structured progression along the climbing route. In this context, they must systematically encode information about holds on the climbing wall in an organized manner and within a brief time frame in order to progress (Seifert et al., 2017).

Heilmann (2021), evaluated WM using the forward Corsi block task in a group of 19 climbers (9 females) of varying abilities. The self-reported climbing ability of Expert climbers ranged from 6c+ to 7b, while novice climbers ranged from 5 to 6a on the French climbing grade scale (Draper et al., 2016). The results revealed that Expert climbers had significantly lower WM capacity (5.33 capacity span) compared to Novice climbers (6.50 capacity span). These findings suggest that Experts rely less on WM and more on their motor skills and experiences in sport climbing.

However, contrasting this Whitaker et al. (2019) found no differences in WM, as measured by the forward Corsi block task, among climbers of different abilities in a sample of 34 climbers (20 females), with self-reported climbing ability ranging from 6a+ to 8b on the French climbing grade scale (Draper et al., 2016).

These divergent findings in WM capacity, as observed by both Heilmann (2021) and Whitaker et al. (2019), suggest that the relationship between WM and climbing is intricate. While the involvement of WM in climbing is clear (Green et al., 2014; Green & Helton, 2011), the overall landscape regarding the association between WM capacity and climbing performance is nuanced by contradictory results (Heilmann, 2021; Whitaker et al., 2019). Notably, research has demonstrated sex differences in WM (Voyer et al., 2017), a decline in WM with age (Baddeley, 2012), and conversely, an apparent protective role of education against age-associated WM declines (Archer et al., 2018). Understanding these additional factors is crucial for a comprehensive grasp of the intricate role of WM in sport climbing, and its impact on performance. Further research is necessary to explore whether divergent evidence could be attributed to potential influences of factors like sex, age, education level on climbers' WM capacity.

Furthermore, within the field of neuroscience, research suggests that the Prefrontal Cortex (PFC) plays a critical role in WM (Chai et al., 2018; Fishburn et al., 2014). In this context, one method employed to gain insights into WM involves the application of Near Infrared Spectroscopy (NIRS) to assess cerebral oxygenation and identify neural activation during WM tasks in the PFC (Sato et al., 2013). Studies have observed that better WM performance is associated with a significant increase in oxygenated hemoglobin (O_2Hb) and deoxygenated hemoglobin (HHb) in the PFC, as measured by NIRS (Fishburn et al., 2014; Ogawa et al., 2014). Conversely, individuals with higher WM capacity may exhibit reduced PFC O_2Hb, indicating greater neural efficiency compared to those with lower WM capacity (Anderson et al., 2018). Therefore, exploring the underlying mechanisms such as the hemodynamic changes in the PFC during a WM task may provide insights into the role of WM capacity in climbing performance.

The present study aims to investigate the relationship between WM capacity and climbing ability, while accounting for potential influencing factors such as sex, age, education level, and climbing experience. Additionally, the study seeks to investigate the temporal dynamics of increased WM load by examining the accumulative changes in PFC hemodynamic responses during WM task. Furthermore, it aims to compare PFC hemodynamic responses during a WM task among different ability groups in climbing, as well as between Females and Males.

Method

Participants

Twenty-eight rock climbers (5 Female), aged from 24 to 49 yrs., volunteered to participate in the study. All participants met the inclusion criteria, which included having at least two years of climbing experience, undergoing at least three months of regular climbing prior to the study, being over 18 years old, and having an absence of injury or conditions that would not be advisable for physical exertion. The exclusion criteria included a history of neurological or psychiatric disorders, the use of medications that could affect vascular function, as well as substance abuse or dependence. The study received ethical approval from the University Ethics Committee. The data for this study were collected from the High-Performance International Rock-Climbing Research Group (C-HIPPER).

Body Composition and Socio-Demographic Characteristics

Body composition variables such as weight, height, and body mass index (BMI) were measured to describe the sample. Specifically, participants were barefoot and wearing underwear. Body weight was measured with a multifrequency bioimpedance (TANITA–MC780MA) (Kyle et al., 2004; Verney et al., 2015), and height was measured in the Frankfurt plane with a telescopic height measuring instrument (Type SECA 225; range, 60–200 cm; precision, 1 mm) (Norton, 2018). The average of the two measurements of height was used for the analyses. BMI was calculated as weight divided by height squared (kg/m^2) (World Health Organization, 2000).

A sociodemographic questionnaire was administered to collect demographic information from participants. This questionnaire included climbing experience (yrs), as well as the climbing days per week to assess the frequency of climbing in a typical week. In the questionnaire, the educational level of the participants was collected as non-university studies (primary and secondary education studies) and university studies (university or higher education studies). The percentage of participants with university education was used to describe the sample.

Self- Reported Climbing Ability

Self-reported climbing ability has been used extensively within the literature (Garrido-Palomino et al., 2020) and validated by Draper et al. (2011). The authors proposed a 3:3:3 rule for reporting climbing grades in research. That is, the climbers' highest grade for which they have completed 3 successful ascents on 3 different routes (at the grade) within the previous 3 months (Draper et al., 2011). In accordance with the Position Statement by the International Rock Climbing Research Association (IRCRA) (Draper et al., 2016), performance grades were converted from French Sport to specific numerical values (IRCRA grades) for all statistical analysis. The sex-specific 75th percentile of on-sight climbing ability was used to describe the sample into Expert (< 75th) and Elite (> 75th) climbers.

Working Memory

The digital version of the Corsi-block task (eCorsi) was administered using an experimentally validated open-source software system called the psychology experiment building language (PEBL; Mueller & Piper, 2014) to measure WM. The WM task was conducted on a laptop with a Lenovo 15-inch color screen in an environmentally controlled exercise laboratory. The WM task began with an encoding period, during which participants were presented with sequences of two squares. The series length gradually increased up to 9 squares, with two sequences were presented for each series length. The squares were flashed on a background black screen for 1,000 milliseconds, with an inter-stimulus interval of 1,000 milliseconds (Figure 1). During the retrieval period, participants were instructed to immediately reproduce the same sequence of blue squares in the same order as they were presented. If at least one square in the sequence was reproduced correctly, the next two trials increased the length of the sequence. The task concluded if participants failed two consecutive trials. Lastly, each WM trial in the eCorsi task was designed to progressively increase cognitive load by extending the sequence length of squares that participants were required to memorize and reproduce. This gradual increase across trials allowed for the assessment of participants' WM capacity under increasing cognitive demand.

Throughout the text, the concept of 'WM load' is operationalized as the complexity of the task in each trial, with the assumption that longer sequences impose a greater cognitive load on participants. This approach provides a quantifiable measure of WM load. The measures recorded to assess participants' performance included WM Capacity, which refers to the number of blocks in the longest correctly reproduced sequence (span score); Error Rate, representing the total number of incorrect responses; Hit Reaction Time for corrects answers, measuring the speed of response for correctly reproduced sequences in milliseconds; and Errors Reaction Time, capturing the speed of response for incorrect answers in milliseconds.

It is important to note that the WM task used in this study focuses on short-term memory and does not directly address the more complex information manipulation processes associated with WM. The task parameters and recorded measurements were based on standardized instructions to ensure consistency and comparability with previous research. The forward version of the WM task was employed, where participants reproduced the sequences in the same order as they were presented. This version of the task was chosen to assess participants' visuospatial working memory capacity in relation to sport climbing performance.

Prefrontal Cortex Perfusion

PFC perfusion was monitored using continuous-wave near infrared spectroscopy (NIRS) NIRO–200NX (Sato et al., 2013). The optode probe was positioned at Fp2 and at Fp1 locations, following the International 10–20 system of electrode placement (Klem et al., 1999). To minimize signal contamination from ambient light, the optode was covered with a dark opaque cloth, as recommended by the manufacturer. NIRs technology relies on the relative transparency of tissue to infrared light and the oxygen-dependent absorption characteristics of hemoglobin. The device operates at three wavelengths (735, 810 and 850 nm) to detect relative perfusion changes.

During the WM task, a filter with a 0.5 Hz cut-off frequency was applied to the Optical Density signals to remove high-frequency noise. The assessed parameters, including the concentration changes in oxygenated hemoglobin (O_2Hb), deoxygenated hemoglobin (HHb), and total hemoglobin (tHb) -referred to as perfusion, as well as the tissue oxygenation index (TOI) during the encoding period, were recorded using input event markers throughout the entire task. For the encoding period, data corresponding to the presentation time of each block sequence were used. Delta ($\triangle$) values for tHb, O_2Hb, HHb, and TOI were calculated as relative changes by comparing each value to a baseline or zero point. This baseline served as the reference point (zero) for quantifying alterations during the task more effectively.

For the NIRS data analysis during the WM task, accumulative hemodynamic changes in the PFC were quantified by comparing the levels of O_2Hb and HHb for each subsequent trial to the baseline established during the first trial. Specifically, these changes were calculated as the difference ($\triangle$) between the values of each trial and those of the baseline. In the comparative NIRS analysis between Expert and Elite climbing groups, hemodynamic changes ($\triangle$) were computed as the difference between the baseline values (first two trials) and those measured during the last two trials of the encoding period.

Statistical Analyses

The normal distribution was using the Shapiro–Wilk goodness-of-fit test, and equal variance using Levene's test. After applying an

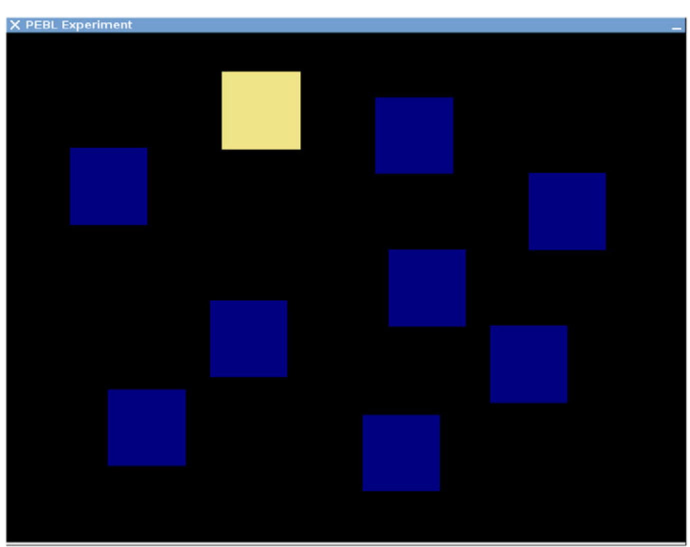

Figure 1. Screenshot of the eCorsi Working Memory Task Interface

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inverse square root transformation of BMI and Climbing Experience, all variables, with the exception of HHb at FP1, were assessed for heteroscedasticity by examining the variance of the residuals.

Descriptive variables were analysed using *t*-tests analysis to assess differences among quantitative variables. Where data did not meet *t*-test assumptions, the non-parametric Kruskal-Wallis test was employed, specifically for HHb at FP1. For categorical variables, the Fisher's exact test was used to examine differences across Expert vs. Elite on-sight climbing categories and between sex (Female vs. Male).

For the main purpose, which focus on the relationship between WM capacity and climbing ability, while accounting for potential influencing factors, linear regression analyses were conducted. Additionally, Error Rate, Error Reaction Time, and Hit Reaction Time were also analyzed as separated indicators of WM performance to provide a comprehensive assessment of its relationship with climbing ability. Confounding variables (sex, age, climbing experience or education level), known to be associated with WM (Archer et al., 2018) and at the same time exhibiting a change in ß coefficients greater than 10%, were included in the regression analyses. Interaction factors (i.e., climbing ability x main confounding variables) were assessed using the chunk test (Greenberg & Kleinbaum, 1985). As no significant interactions were observed, all climbers were analyzed together. Multicollinearity was assessed in all models used in this study. The variance inflation factor was below 10, and averaged variance inflation factor was close to 1 (Myers, 1990), indicating the absence of multicollinearity. The relationship between WM Capacity (including indicators of its performance: Error Rate, Error Reaction Time, and Hit Reaction Time), and Climbing Ability was examined unadjusted and using four adjustment models. Model 1 was adjusted for sex, Model 2 was adjusted for Sex and Age, Model 3 was adjusted for Sex and Climbing Experience, and Model 4 was adjusted for Sex and Education Level. Additionally, an analysis of residuals was conducted for each model to verify the assumption of normally distributed residuals. Furthermore, a sensitivity analyses was conducted among Male participants only to assess the robustness of the associations between WM Capacity and Climbing Ability, considering the limited number of Female participants in this study.

In pursuit of our secondary objective, that focus on the temporal dynamic of increased WM load, we examined the accumulative changes in PFC hemodynamic responses across WM trials. To this end, a Pearson correlation analyses (and Spearman for HHb at FP1) was conducted to assess the relationship between WM load across trials and changes in O_2Hb and HHb levels in both the left and right PFC. Furthermore, to compare PFC hemodynamic responses during the WM task between climbing ability groups (Expert vs. Elite) and sex (Female vs. Male), we employed the Fisher's exact test to analyze categorical differences. This was complemented by *t*-test analyses, and where necessary due to non-normal distributions, the non-parametric Kruskal-Wallis test, particularly for HHb at FP1.

All statistical analyses were performed using STATA Version 13.1 (Stata Corp, College Station, TX, USA).

Results

Descriptive characteristics of the study population, including anthropometric and demographic data and WM measurements, are presented for the entire sample, stratified by climbing ability (Expert vs. Elite) and sex (Female vs. Male) in Table 1. The results of normal distribution and equal variance testing for all variables, as well as the chunk test for the analysis of interaction factors, are presented in the Supplemental Material, Tables S1 and S2.

The mean age of the participants was 37.5 years, with an average climbing experience of 14.0 years (range, 3 to 30 years). On-sight climbing ability levels ranged from 5+ to 7c+ on the French scale). Specifically, Expert climbers reported climbing abilities ranging

Table 1. Descriptive Characteristics, Working Memory Task Measures (Mean ± Standard Deviation), and T-test Analyses of the Entire Sample, Stratified by Climbing Ability and Sex

	All sample (*n* = 28)	Expert (*n* = 19)	Elite (*n* = 9)	p	Female (*n* = 5)	Male (*n* = 23)	*p*
Age (years)	37.5 ± 6.6	37.3 ± 7.0	37.9 ± 6.3	.834	38.1 ± 3.8	37.3 ± 7.3	.811
Weight (kg)	69.9 ± 10.9	72.9 ± 10.7	64.1 ± 9.3*	.047	55.4 ± 5.4	73.2 ± 9.0***	<.001
Height (m)	172.8 ± 8.4	173.4 ± 6.8	171.6 ± 11.3	.622	159.8 ± 4.6	175.7 ± 5.9***	<.001
Body Mass Index (kg/m2)^	23.4 ± 3.2	24.2 ± 3.4	21.7 ± 1.2*	.038	21.7 ± 2.2	23.8 ± 3.3	.184
Education Level (%)[a]	39.3	44.4	30	.689[b]	16.7	45.5	.355[b]
Climbing Experience (years)^	14.0 ± 9.3	12.1 ± 8.6	17.6 ± 10.0	.179	11.7 ± 9.5	14.6 ± 9.4	.277
Climbing Days per Week	1.8 ±.9	1.9 ±.9	1.6 ±.8	.391	1.2 ±.8	2.0 ±.8*	.043
On–sight Climbing Ability range (IRCRA scale)	16.27 ± 3.27	14.84 ± 2.67	19 ± 2.53***	<.001	13.16 ± 2.92	17.09 ± 2.89**	.007
Working Memory measures							
Working Memory Capacity (Span score)	5.6 ±.8	5.8 ±.8	5.2 ±.7	.087	5.5 ±.9	5.6 ±.8	.754
Error Rate (Number of incorrect responses)	3.0 ±.9	3.2 ±.8	2.7 ± 1.0	.063	3.0 ± 1.2	3.0 ±.9	.306
Hit Reaction Time (Milliseconds)	590.3 ± 116.3	582.2 ± 111.8	607.5 ± 130.5	.601	559.7 ± 54.3	597.0 ± 125.7	.527
Error Reaction Time (Milliseconds)	655.4 ± 195.3	608.6 ± 194.4	754.1 ± 165.8	.064	551.5 ± 77.3	677.4 ± 195.3	.195

Note. *p*-values for comparisons between climbing ability groups and sex are based on *t*-test for continuous variables and Fisher exact test for categorical variables.
[a]Participant with university studies.
[b]Fisher exact test analysis.
^Inverse square root transformation.
* *p* <.05. ** *p* <.01. ****p* <.001 indicating significant different the from Expert climbers and differences between sex.

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Table 2. Multiple Lineal Regression Coefficients Examining the Relationship of Working Memory and Climbing Ability

	b	β	95% IC		t	p	R^2	Adj R^2
			LL	*UL*				
Working Memory Capacity (Span score)								
Unadjusted	–.356	–.088	–.18	.01	–1.94	.063	.127	.093
Model 1. Adjusted for sex	–.558	–.138	–.25	–.03	–2.64	.014*	.222	.159
Model 2. Adjusted for sex and age	–.535	–.132	–.25	–.02	–2.38	.026*	.225	.129
Model 3. Adjusted for sex and climbing experience (years)	–.581	–.153	–.27	–.02	–2.41	.024*	.218	.116
Model 4. Adjusted for sex and education level	–.499	–.118	–.23	–.01	–2.20	.038*	.213	.111
Error Rate (Number of incorrect responses)								
Unadjusted	–.210	–.06	–.16	–.05	–1.09	.285	.04	.007
Model 1. Adjusted for sex	–.300	–.081	–.21	.05	–1.29	.207	.155	.091
Model 2. Adjusted for sex and age	–.350	–.095	–.23	.04	–1.43	.167	.081	–.034
Model 3. Adjusted for sex and climbing experience (years)	–.332	–.090	–.24	.06	–1.22	.234	.064	–.058
Model 4. Adjusted for sex and education level	–.408	–.110	–.24	.02	–1.71	.101	.127	.013
Error Reaction Time (Milliseconds)								
Unadjusted	.511	30	9.68	50.32	3.04	.005**	.262	.233
Model 1. Adjusted for sex	.534	31.310	6.49	56.13	2.30	.016*	.263	.204
Model 2. Adjusted for sex and age	.527	30.888	4.31	57.47	2.40	.025*	.263	.171
Model 3. Adjusted for sex and climbing experience (years)	.725	41.636	16.17	67.10	3.38	.003**	.380	.299
Model 4. Adjusted for sex and education level	.484	28.089	1.77	54.41	2.21	.037*	.267	.171
Hit Reaction Time (Milliseconds)								
Unadjusted	.136	4.752	–9.20	18.70	.70	.490	.019	–.019
Model 1. Adjusted for sex	.097	3.374	–13.65	20.40	.41	.687	.022	–.056
Model 2. Adjusted for sex and age	.083	2.912	–15.31	21.14	.33	.744	.023	–.099
Model 3. Adjusted for sex and climbing experience (years)	.299	10.024	–8.18	28.23	1.14	.266	.066	–.056
Model 4. Adjusted for sex and education level	.128	4.561	–13.71	22.83	.52	.611	.052	–.072

Note. Data are presented as standardized regression coefficient (b), unstandardized regression coefficient (β), 95% confidence interval (95% CI), lower confidence interval (LL), upper confidence interval (UL) and P-value (*p*).
* *p* <.05.***p* <.01. ****p* <.001 indicating statistically significant associations.

from 5+ to 7a+, while Elite climbers ranged from 6c to 7c+ in Elite climbers (75th percentile, 7a+). Among Male participants, climbing ability ranged from 6a+ to 7b for Experts, and from 7b+ to 7c+ for Elites, with the 75th percentile at 7b. Female participants reported climbing abilities ranged from 5+ to 6c for Expert and from 6c+ to 7a for Elite, with the 75th percentile at 6c. Onsight climbing ability was significantly higher for Elite compared to Expert ($p < .001$) and for Male compared to Female ($p < .001$). Additionally, Males climbed significantly more days per week than Females ($p < .05$). Fisher's exact tests revealed no significant differences related to Education Level between Expert and Elite ($p = .689$) or between Sex ($p = .355$).

In Table 2, multiple regression coefficients (b), unstandardized regression coefficient (β), 95% confidence intervals (95% CI), and P-values (*p*) examining the relationship between WM and climbing ability are presented. Additionally, the analysis of residuals confirms normal distribution and verifies the absence of outliers or highly influential points for each model (see Supplemental Material, Figure S1). The analysis revealed that in the unadjusted model, climbing ability did not significantly predict WM capacity, $F(1, 26) = 3.77$, $R^2 = .127$; $p = .063$. For the variable of interest, climbing ability, a one-unit change was associated with a decrease of .088 in WM capacity (β = -.088), with a *t*-statistic of -1.94 and $p = .063$) (see Table 2 and Figure 2). Upon examination of the influence of confounding factors, significant predictors of the negative association between WM capacity and climbing ability were found. Specifically, Sex was a significant predictor, β = -.138, $t(25) = -2.64$, $p = .014$. Additionally, the combination of Sex with climbing experience was also significant, β = -.153, $t(24) = -2.41$, $p = .024$. When considering Sex alongside Age, the model showed significant results, β = -.132, $t(24) = -2.38$, $p = .026$. Similarly, including Education Level showed significant associations, β = -.118, $t(24) = -2.20$, $p = .038$. These coefficients indicate the extent to which each predictor variable influences WM capacity, assuming other predictor variables are held constant.

Comparable results were obtained when analysing the association between WM measurements and Climbing Ability exclusively in Male participants ($n = 23$). For instance, the association between WM Capacity and Climbing Ability was $F(1, 21) = 10.87$, $R^2 = .341$, $p = .003$ (see Supplemental Material, Table S3).

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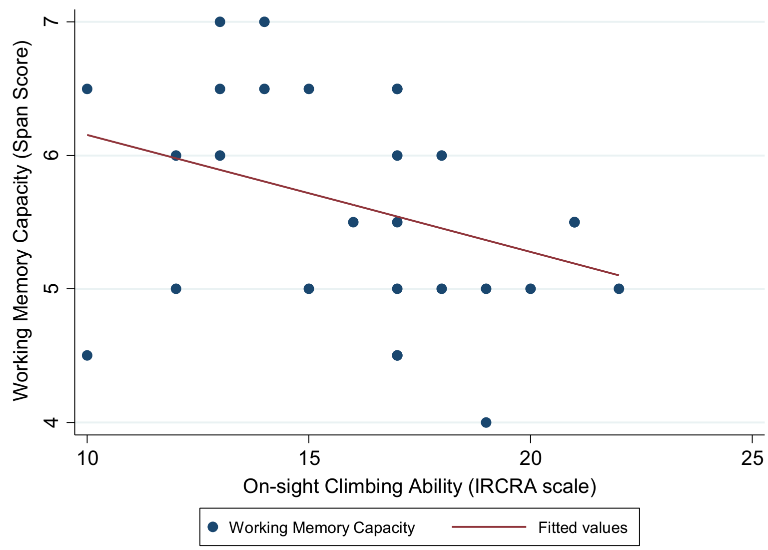

Figure 2. Linear Relationship between Working Memory Capacity and Climbing Ability

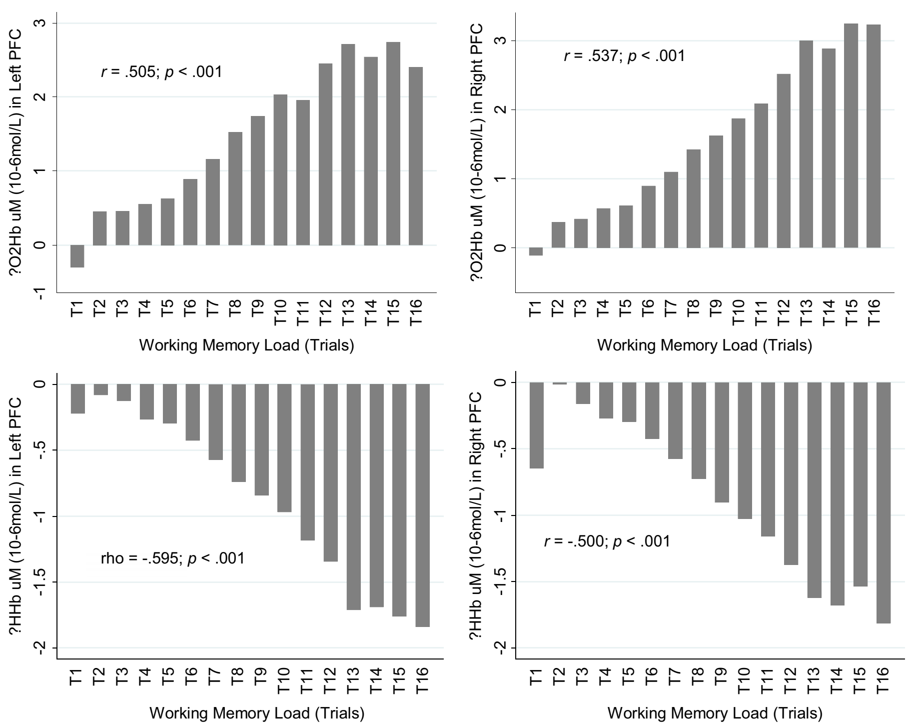

Figure 3. Accumulated Hemodynamic Changes in Left and Right Prefrontal Cortex across Trials during the Working Memory Task in the Entire Sample

Regression analysis revealed positive significant associations between Error Reaction Time and Climbing Ability, $F(1, 26) = 9.21$, $R^2 = .262$, $p = .005$. A one-unit change in climbing ability was associated with an increase of 30 milliseconds in reaction time in response to errors, $\beta = 30$, $t(26) = 3.04$, $p = .005$. This significant association persisted across all models after adjusting for confounding factors. Specifically, Sex was a significant predictor, $\beta = 31.310$, $t(25) = 2.30$, $p = .016$, as was the combination of Sex with Climbing Experience, $\beta = 41.636$, $t(24) = 3.78$, p = .001). Additionally, Sex combined with Age, $\beta = 30.888$, t (24) = 2.40, $p = .025$, and Sex combined with Education Level, $\beta = 28.089$, $t(24) = 2.21$, $p = .037$, were significant predictors of the positive association between Error Reaction Time and Climbing Ability.

Non-significant associations were found for Hit Reaction Time and Climbing Ability (p >.05). Similarly, no significant associations were found between Error Rate and Climbing Ability (p >.05). However, when adjusted for Education Level in men, there was a significant association, $\beta = -.146$, $t(19) = -2.42$, $p = .026$. This indicates that Education Level is a significant predictor of the negative association between Error Rate in the WM task and Climbing Ability (see Supplemental Material, Table S3).

In alignment with our secondary objective, correlation analyses revealed a significant positive correlation between WM load and O_2Hb in both the right and left PFC across each trial, with coefficients of $r = .537$ ($p < .001$) and $r = .505$ ($p < .001$), respectively. Conversely, a negative correlation was observed between WM load

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Table 3. *Hemodynamic Changes and T-test Analyses* in *the Prefrontal Cortex During the Working Memory Task across the Entire Sample, Categorized by Climbing Ability (Elite vs. Expert) and Sex*

	All sample (*n* = 28)	Expert (*n* = 19)	Elite (*n* = 9)	*p*	Female (*n* = 5)	Male (*n* = 23)	*p*
Left Prefrontal Cortex (FP 1)							
△tHb (uM)	1.14 ± 1.41	.76 ± 1.44	1.94 ± 1.00*	.037	.59 ± 1.58	1.26 ± 1.38	.346
△O_2Hb (uM)	2.48 ± 1.66	2.42 ± 1.91	2.60 ± 1.04	.798	1.17 ± 1.66	2.76 ± 1.55	.050
△HHb (uM)	–1.20 ±.84	–1.45 ±.87	–.65 ±.39*	.015	–.58 ±.27	–1.33 ±.86*	.025
△TOI (%)	.80 ± 1.15	.89 ± 1.28	.60 ±.83	.55	.13 ±.70	.94 ± 1.19	.159
Right Prefrontal Cortex (FP 2)							
△tHb (uM)	1.08 ±1.53	1.17 ± 1.51	0.88 ± 1.66	.64	.95 ± 1.06	1.11 ± 1.64	.837
△O_2Hb (uM)	2.43 ± 1.75	2.82 ± 1.81	1.59 ± 1.36	.082	1.37 ± 1.14	2.66 ± 1.80	.140
△HHb (uM)	–1.24 ±.75	–1.50 ±.72	–.71 ±.54**	.008	–.42 ±.28	–1.42 ±.70**	.005
△TOI (%)	.63 ± 1.44	.73 ± 1.65	.43 ±.89	.612	–.03 ±.93	.78 ± 1.50	.262

Note. Data presented as mean ± standard deviation. Hemodynamic changes (△) were calculated as resulting of the difference between baseline values (two first trials) and those sampled during the last two trial of working memory task.
[a] Kruskal wallis test.
uM = 10^{-6}mol/L.
**p* <.05. ***p* <.01. ****p* <.001 indicating significant different the from Expert climbers and differences between sex.

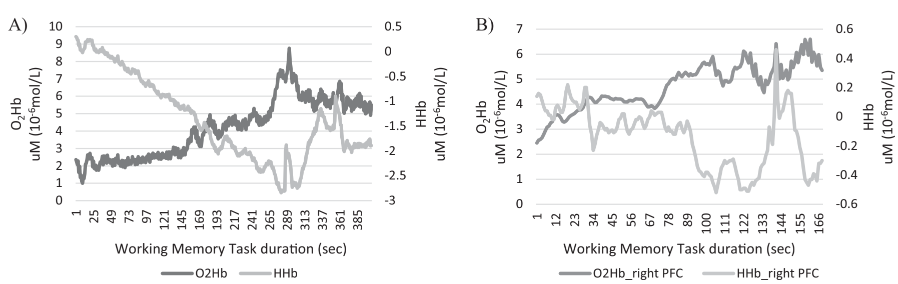

Figure 4. An example of the Oxi- and De-Oxygenation Changes in Right Prefrontal Cortex of Male with Different Climbing Ability and Working Memory Capacity during Working Memory Task.
Note. (A) Expert Male Climber (6b+ On-Sight Climbing Ability) with 7 Span of Working Memory Capacity. (B) Elite Male Climber (7b+ On-Sight Climbing Ability) with 4 Span of Working Memory Capacity.

and HHb levels, with coefficients of *r* = -.500 (*p* < .001) for the right PFC and rho = -.595 (*p* < .001) for the left PFC, across each trial (See Figure 3).

Additionally, hemodynamic changes (mean and standard deviation) in the PFC during the WM task of the entire sample, categorized by climbing ability and sex are presented in Table 3. Significant differences were found between Expert and Elite climbers in tHb levels at Fp1, Mean Differences (MD) = -1.18, 95% Coefficient Interval (CI) [-2.28, -.079], *p* = .037; and HHb levels in both Fp1, MD = -.80, 95% CI [-1.43, -.71], *p* = .015; and Fp2, MD = -.78, 95% CI = [-1.34, -.23], *p* = .008; during the WM task. Sex differences were also observed in HHb levels at Fp1, MD = .75; 95% CI [-.06, 1.56]; *p* = .025; and Fp2, MD = 1; 95% CI [.33, 1.67]; *p* = .005.

Figure S2 in the Supplemental Material illustrates the changes in HHb levels in the left and right PFC for Expert vs. Elite climbers (upper panels) and Male vs. Female climbers (lower panels) after completion of the WM task. The box plots show the distribution of HHb changes, indicating differences in cerebral blood flow and de-oxygenation between the groups. A greater change in HHb levels suggests a higher PFC activity due cognitive load. Lastly, Figure 4 illustrates an example of the changes in oxygenation and deoxygenation in the right PFC of two climbers differing in climbing ability (Expert vs. Elite) and in WM capacity. This visual comparison aims to showcase the differential patterns of activation between climbers of various skill levels under their maximum WM load.

Discussion

Rock climbing is a physically demanding activity that requires individuals to navigate complex routes, make quick decisions, and execute precise movements to ascend rock faces successfully. These cognitive demands necessitate the effective utilization of WM, which enable climbers to hold and use information about their environment and plan their actions accordingly. WM capacity is believed to play a crucial role in supporting the cognitive skills necessary for climbers. Thus, the primary objective of the present study is to investigate the relationship between WM Capacity and Climbing Ability, considering potential confounding factors (Sex, Age, Education Level or Climbing Experience). Furthermore, the study aims to compare differences in WM Capacity and PFC hemodynamic responses during a WM task between Experts and Elite climbers, as well as between Female and Male. Our findings revealed no significant association between WM capacity and climbing ability. However, when controlling for confounding factors, we observed a significant negative association between WM capacity and on-sight climbing ability. These results are consistent with Heilmann (2021), who demonstrated that Novice climbers outperformed Expert climbers in a WM task (eCorsi task) that quantified WM span score. These findings may provide an explanation for the divergent results obtained by Heilmann (2021) and Whitaker et al. (2019), highlighting the significance of sex, age, education level, and climbing experience in the evaluation of WM in climbers.

Two hypotheses were proposed to explain these findings. First, it is possible that WM capacity serves as an adaptive function for self-preservation, where lower-ability climbers may perform less effectively due to naturally greater WM capacity. Previous literature has suggested that higher WM capacity may lead to increased visual attention in detecting dangerous stimuli (Wood et al., 2016) and, emotional stimuli in WM negatively interfere with climbing performance (Green et al., 2014). Therefore, our first hypothesis suggests that climbers with higher WM capacity may prioritize threatening information (i.e., falling distance) in WM, which could impair their climbing performance. The second hypothesis, based on the "embedded-processes model of WM" (Cowan, 2010), posits that higher-skilled climbers develop a relatively smaller WM capacity but compensate for it with better attentional control and information stored in short- and long-term memory through repeated practice of climbing (climbing experience). This model suggests a dynamic relationship between WM, attention and long-term memory, where a smaller WM capacity may be a strength resulting from enhanced learning abilities, and compensatory mechanisms of attentional control and long-term memory would contribute to more efficient WM functioning (Cowan, 2010). Previous findings support this hypothesis, indicating that skilled climbers employ a behavioral gaze strategy (Grushko & Leonov, 2014), exibit better attentional control (Garrido-Palomino et al., 2020), and have superior short-term memory for recalling holds and movement sequences (Whitaker et al., 2019).

Interestingly, our results showed a positive relationship between error reaction time and climbing ability (Table 2). Previous research has suggested that larger reaction time to wrong answers reflects the detection and processing of cognitive conflict, including conflict resulting from errors (Botvinick & Braver, 2015). It has also been proposed than error recognition is loaded into WM during motor performance or motor learning to update the motor plan for subsequent actions (Seidler et al., 2012). Larger error's reaction time may indicate a more efficient behavior of WM for error detection in Elite climbers compared to Expert climbers (Falkenstein et al., 2000).

Regarding our secondary aim, we first examined the overall changes in PFC hemodynamic responses as the WM load increased across trials. The analyses revealed a consistent pattern of increased O_2Hb and HHb levels in response to the rising WM load, as shown in Figure 3. These patterns support the hypothesis of a progressive increase in cognitive effort as the WM demands intensify, highlighting the cognitive challenge imposed by the WM task across all participants. Following this general observation, we further investigated whether these hemodynamic responses differed between groups of climbers with varying expertise, i.e., Expert and Elite. Our results indicated significant differences, with Expert climbers showing decreased HHb at both Fp1 and Fp2 as WM load increased. These findings suggest increased delivery or increased metabolic demand in the PFC, reflecting superior WM performance in Expert climbers. These results are consistent with previous functional magnetic resonance imaging studies that have found positive correlation between better WM performance and increased PFC activation (McNab & Klingberg, 2008; Causse et al., 2017). The observed hemodynamic changes likely reflect neural activity in response to the mental workload and greater difficulty experienced by Expert climbers during the WM tasks. Additionally, the differences in PFC hemodynamic responses between Male and Female climbers during the WM task, in the absence of WM capacity differences, align with previous studies supporting sex-specific PFC activation in WM function (Li et al., 2010). Overall, our study sheds light on the role of WM capacity in climbers' performance and may have practical application, particularly in the early stages of learning. In line with the theory of the "embedded-processes model of WM" (Cowan, 2010), enhancing short- and long-term memory, as well as attention training, during the initial learning phase, could contribute to more efficient functioning of WM in climbing. This could involve strategies such as memorizing routes and movements' sequences or learning to focus attention on critical elements for climbing progression. However, future research is needed to confirm these potential benefits and explore WM capacity is like in Female climbers of varying ability. By considering these factors, climbers, coaches, and trainers can optimize their training approaches and improve in climbing activities.

It is essential to address the nuanced relationship between PFC hemodynamic responses, climbing ability, and sex differences observed in our study. We have rigorously controlled for climbing ability by categorizing participants into Expert and Elite groups based on a sex-specific 75th percentile, ensuring that our analyses accurately reflect the interplay between climbing proficiency and sex. This approach allows us to discern whether observed hemodynamic changes are attributable to climbing ability or inherent sex differences. Notably, despite the smaller sample size of Female climbers within each category, their inclusion is imperative for a holistic understanding of cognitive function across sex in climbing. This decision underscores our commitment to sex inclusivity in sports science research, aiming to provide insights that are representative of the entire climbing community. Our analyses and discussions are crafted to highlight these considerations, aiming to mitigate potential biases and contribute to a more comprehensive understanding of the role of WM in climbing performance.

In order to fully contextualise the findings, we need to recognise both the limitations and strengths of this study. Firstly, the sample size was relatively small, which may limit the generalizability of the findings. A larger sample would provide a more representative depiction of the climbing population and bolster the robustness of the results. Secondly, the cross-sectional design employed in this study prevents the establishment of causal relationship. A longitudinal or experimental design would offer a deeper understanding of the influence of WM capacity on climbing performance. Additionally, while efforts were made to control for confounding factors such as, sex, age, education level, and climbing experience, it is important to acknowledge the potential influence of uncontrolled factors, including mood, motivation, and general cognitive abilities. Despite these limitations, the study also possesses strengths. Firstly, it successfully controlled for several confounding factors, enhancing the internal validity of the study, and enabling a more accurate analysis of the relationship between WM capacity and climbing performance. Secondly, this study contributes to an emerging area of research by replicating and expanding upon a previous study on WM in the climbing field (Heilmann, 2021). By replicating the findings of Heilmann's study, our research provides further evidence and insights into the influence of confounding factors on

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WM capacity in the context of climbing performance. Lastly, the study explored additional measures related to WM capacity, such as error rate, reaction time and hemodynamic responses in the PFC. These additional measures provide a more comprehensive understanding of the relationship between WM capacity and climbing performance. Furthermore, future research should investigate whether the observed differences in WM between climbers of different skill levels, as measured in a laboratory task, are maintained when measured in a sport context, such as climbing on a rock or artificial climbing wall. This would provide valuable insights into transferability of WM capacity from controlled laboratory setting to real-world climbing scenarios.

To summarize, this study has made a significant contribution to understanding the complex interplay between cognitive function and climbing performance. It has uncovered nuanced differences in working memory capacity among climbers, with sex, age, education level, and climbing experience emerging as significant predictors. Notably, our analyses suggest that on-sight climbing ability is intricately linked to working memory, showing that Expert climbers exhibited higher working memory capacity compared to Elite Climbers, with this association becoming significant upon adjusting for these influencing factors. This underscores the multifaceted nature of climbing, where cognitive processes are as critical as physical capabilities. Additionally, the observed variations in prefrontal cortex hemodynamic responses between Expert and Elite climbers provide a physiological basis for these differences in working memory capacity based on climbing ability. Overall, these findings align with the "embedded-processes model of working memory", suggesting that a lower limit of working memory may indicate a more efficient cognitive system in the successful climbers. Sex-specific differences in prefrontal cortex activation patterns also emerged, pointing to potential differences in how male and female climbers utilize their cognitive resources during working memory tasks. These insights pave the way for targeted cognitive training interventions that could enhance climbing performance, particularly through the strategic management of working memory load. While further research is indeed necessary to deepen our understanding, climbers, coaches and trainers should consider the type and amount of information climbers load into their working memory during climbing to prevent errors, enhancing short- and long-term memory and attention training in early stages.

Supplementary material. To view supplementary material for this article, please visit http://doi.org/10.1017/SJP.2024.25.

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Data sharing. The authors agree to make the raw data supporting the results or analyses presented in their paper available upon reasonable request.

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