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Mechanisms underlying superior memory of skilled climbers in indoor bouldering

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ABSTRACT

Introduction: Bouldering is an Olympic climbing discipline that encompasses short climbing sequences, referred to as boulders, set up on low-height bouldering walls. Memory plays a critical role in bouldering, as it allows climbers to develop climbing strategies, to mentally rehearse climbing movements, and to recall climbing holds of boulders. This study extends previous research on memory in climbing and bouldering with the purpose to elucidate potential mechanisms underlying superior memory abilities of skilled climbers.
Methods: Sixty climbers with intermediate ($n = 20$), advanced ($n = 20$), or elite ($n = 20$) skill levels were tasked to memorise the climbing holds and movements of a boulder, set up on a spray wall and demonstrated by a bouldering expert.
Results: Findings revealed a positive relation between the participants' bouldering skills and sport-specific movement knowledge and both, the number of climbing holds and movements they were able to memorise following a two-minute rehearsal period.
Conclusion: Consistent with previous research, bouldering expertise is positively associated with the ability to memorise domain-specific information. Superior memory abilities among skilled climbers appear to be associated with climbing-specific movement knowledge, coupled with better mental visualisation and increased attentional focus towards functional aspects of boulders.

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KEYWORDS
Movement knowledge; climbing; route previewing; chunking; mental simulation

The inclusion of competitive climbing in the Tokyo 2020 Olympic programme has contributed to the growing popularity of the sport (Mckellar et al., 2023; Winkler et al., 2023). Olympic climbing competitions comprise three disciplines: lead climbing, in which athletes attempt routes of at least 15 metres in length; speed climbing, in which time it takes to climb a standardised route is decisive; and bouldering, in which climbers must solve a series of short climbing sequences referred to as boulders (Hatch & Leonardon, 2023). The main distinction between lead climbing and bouldering is that climbing routes are considerably longer, and competitors climb a single route for which they have one attempt (called "onsight"). In contrast, boulders are notably shorter (typically containing four to eight handholds), and athletes have multiple attempts to climb four to five boulders per round within the time limitation.

Over the last two decades, the increasing popularity of climbing in general and bouldering in particular has also sparked research interest in domain-specific perceptual and cognitive skills. For the modality of bouldering, recent studies highlight that bouldering expertise is associated with climbers' decision-making skills (Medernach et al., 2021), their perceptual judgement accuracy of action capabilities (Whitaker et al., 2019), and their ability to find creative motor solutions (Künzell et al., 2021). Perceptual-cognitive skills are critical for athletes to process environmental information and to integrate perceived stimuli from the current situation with existing knowledge in order to plan, select, and execute appropriate and goal-directed motor actions (Marteniuk, 1976; Roca & Williams, 2016). That is, perceptual and cognitive skills function as mediators between environmental demands and corresponding motor skills required for movement execution. In climbing, perceptual-cognitive skills are crucial for processing relevant information like the reachability and graspability of climbing holds during route previewing (Sanchez et al., 2012), as well as for appropriate route management (Sanchez et al., 2019) and decision-making (Medernach et al., 2021) during climbing.

Route previewing refers to the visual processing of a route or boulder that climbers perform prior to climbing (Sanchez et al., 2012). Route previewing is considered crucial to achieving optimal climbing performance, as it permits climbers to interpret visual sensory inputs, to identify potential climbing strategies, and to develop appropriate motor responses (Medernach et al., 2021; Whitaker et al., 2019). For instance, Sanchez and colleagues (Sanchez et al., 2012) found that previewing routes contributed to reduced and shorter non-movement times during climbing. In a more recent study investigating bouldering performance, Morenas and colleagues (Morenas et al., 2021) addressed the effect of different types of previewing (no preview, video-model, and real-mode). They observed that real-mode route previewing contributed to more successful completions of boulders, while climbers exhibited more failed climbing attempts when not performing a preview.

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Climbing proficiency is also associated with movement knowledge (Medernach et al., 2021; Sanchez et al., 2019), which pertains to the repertoire of climbing movements that climbers acquire through deliberate practice and long-term climbing experience (Fleming & Hörst, 2010; Sanchez et al., 2019). Ferrand et al., (2006) examined impediments to achieving successful climbing performance as perceived by elite competitors, who identified lack of climbing route knowledge as a self-handicap in climbing competitions. Moreover, Sanchez and colleagues (Sanchez et al., 2019) surveyed expert climbing coaches who identified domain-specific movement repertoire as a crucial performance factor in sport climbing. As motor actions typically involve integrating perceptual information processed in short-term memory with movement patterns stored in long-term memory (Cowell et al., 2019; Roca & Williams, 2016), an extensive movement repertoire is compulsory to accurately interpret climbing opportunities, to anticipate climbing movements, and to produce embodied motor simulations.

Research on climbing and bouldering suggests that climbing proficiency also relates to domain-specific visual memory skills, resulting in superior recall abilities after route previewing (Pezzulo et al., 2010; Whitaker et al., 2019). Boschker et al. (2002) were among the first to observe that skilled climbers recalled the position and orientation of climbing holds that they previously perceived more rapidly and accurately than their less experienced counterparts. More recently, Whitaker et al., (2019) examined how climbing expertise affects visual memory performance of climbers. They observed that skilled climbers exhibited improved visual memory of climbing holds compared to less skilled climbers, following a one-minute route preview and after attempting three boulders of their choice.

Memory plays a decisive role in bouldering (Whitaker et al., 2019); it enables climbers to develop appropriate climbing strategies following unsuccessful climbing attempts, to mentally rehearse climbing movements, and to recall the climbing holds of a boulder after route previewing. To illustrate, competitors in IFSC (International Federation of Sport Climbing) finals are provided with a collective observation period to preview four boulders consecutively, each for two minutes; remembering the climbing holds can be critical to mentally visualise the climbing movements in the isolation zone. Additionally, in their daily bouldering practice, climbers frequently use spray walls, which consist of small-sided and typically overhanging climbing walls equipped with numerous climbing holds. In contrast to training walls such as the Kilter board, spray walls are not equipped with LEDs that guide climbers through a boulder. That is, climbers must visualise and memorise the holds of each boulder prior to making an attempt. In this context, it is noteworthy that climbers commonly employ the observational learning approach, originally proposed by Bandura (1977), when exercising on spray walls, as well as in bouldering more generally. This approach involves acquiring and developing sport-specific skills by observing, memorising, and mimicking the problem-solving strategies and motor actions of other climbers.

Although the importance of memory in bouldering is widely acknowledged, there is still a lack of research in this field, and mechanisms that account for higher memory aptitudes among experts warrant further elucidation. Evidently, the inability to recall climbing holds and movements is ascribed to the restricted storage capacity and duration of short-term memory (Cowan, 2008), a concept notably popularised by Miller (1956). Miller proposed that the span of absolute judgement, immediate memory, and subitising is about seven, plus minus two items in length. Since Miller's seminal work on the topic, subsequent literature has proposed that the capacity of short-term memory is limited to approximately four to nine units of information, depending upon inter-individual variability, applied memory strategies, and the boundary conditions of observation (Cowan, 2001; Rouder et al., 2008).

Besides the limited storage capacity of short-term memory, Boschker and colleagues (Boschker et al., 2002) posited that superior memory abilities in skilled climbers are linked to the focus of attention during route previewing. The authors contended that accomplished climbers focus their attention more on functional aspects of the climbing wall to perceive climbing opportunities while previewing a route and hence benefit from better recall abilities than novice climbers who concentrate more on structural features, such as the size and orientation of climbing holds. Later, Pezzulo et al., (2010) observed that superior memorisation abilities of skilled climbers occurred solely on a difficult route that suited their performance level, but vanished when climbers encountered both an easy and impossible route. The authors assumed that if the difficulty level of a climbing route surpasses climbers' motor skills, it may hinder their ability to mentally visualise the climbing movements, leading to a decrease in memory performance. Similarly, Sugi and Ishihara (2019) investigated the impact of movement simulation on the memory abilities of climbers. They observed that memory of route characteristics was more accurate on a climbable route in terms of difficulty compared to a motorically impossible route. That is, the feasibility of a route affects the retention of its features.

In the study conducted by Whitaker and colleagues (Whitaker et al., 2019), the authors argued that climbers' superior memory abilities may be linked to their knowledge of climbing movements, allowing them to chunk climbing movements into a meaningful climbing sequence. The concept of chunking dates back to Miller (1956) and enables individuals to enhance their processing and recall abilities in short-term memory by clustering individual pieces of information into a larger and meaningful unit (Thalmann et al., 2019). In this context, the limitations of short-term memory can be mitigated by implementing knowledge acquired through past experiences, stored in long-term memory, and accessed through perceptual discrimination processes (Cowan, 2008). As such, the acquisition of high-level knowledge structures has a beneficial impact on short-term memory and recall ability (Sala & Gobet, 2017).

Given the current lack of research on memory in indoor bouldering, this study extends previous work on memory in sport climbing (Boschker et al., 2002; Pezzulo et al., 2010) and bouldering (Whitaker et al., 2019) with the purpose to elucidate potential mechanisms underlying superior memory abilities of climbing experts. In our experiment, we exposed 60 climbers with intermediate, advanced, or elite ability levels to a novel boulder of advanced difficulty (20 IRCRA points, see Draper et al., 2016), set on a spray wall with numerous climbing holds varying in size, shape, and colour. A bouldering expert gave a practical demonstration of the boulder, and participants were instructed to memorise the holds used and the movements performed by the expert. In line with Whitaker et al., (2019), we hypothesised (hypothesis 1) that bouldering expertise would be positively associated with the ability to memorise domain-specific information, and that advanced and elite climbers would thus recall more holds and movements than intermediate climbers. Furthermore, extending Pezzulo et al., (2010) and Sugi and Ishihara (2019), we hypothesised (hypothesis 2) that participants' memory capacity would be related to the feasibility of the boulder. That is, intermediate climbers would be impeded from mentally visualising the climbing movements and performing embodied motor simulations because the difficulty of the boulder is beyond their skill level, leading to a lower number of recalled climbing holds and movements. Finally, extending Whitaker et al., (2019), we hypothesised (hypothesis 3) that memory in bouldering would be associated with domain-specific movement knowledge. This is because superior movement knowledge allows skilled climbers to better compare sensory input with patterns stored in long-term memory, which helps them to better identify familiar movement patterns (Cowell et al., 2019; Sala & Gobet, 2017) and thus to be more successful at clustering the perceptual stimuli into a meaningful unit (Cowan, 2008).

Method

Participants

Sixty male climbers, who were recruited from local climbing associations and commercial climbing centres, voluntarily participated in the study. Participants provided written informed consent, and the study was conducted in compliance with the World Medical Association and received ethical approval from the University Ethics Committee (ID 057/2020). Participants were at least 18 years old, healthy, and had no injuries that could have potentially impacted their bouldering performance during the experiment. As spray walls are not advisable for inexperienced climbers and participants were required to physically attempt the boulder, non-climbers and beginners were excluded from the study. Furthermore, we sought to ensure a high consistency in body characteristics among the study groups to best limit potential factors, such as body height and reachability of holds, that could affect participants' bouldering performance; this resulted in no female climbers participating in our experiment.

Participants were assigned to the intermediate group (INT; $n = 20$), the advanced group (ADV; $n = 20$), or elite group (ELI; $n = 20$) according to their scores on the IRCRA (International Rock Climbing Research Association) scale. This widely accepted scale allows climbing grades to be converted into a numerical system, and is considered reliable and valid for classifying climbing ability and thus assigning climbers to specific ability groups (Draper et al., 2016). The most difficult boulder that participants self-reported they were able to climb was retained as IRCRA scores. As shown in Table 1, differences between the study groups were non-significant for age, body weight (measured using a Seca 760 scale in T-shirt and shorts), and height (measured using a Seca 213 stadiometer). Conversely, the three study groups differed in terms of the participants' years of bouldering experience and their number of bouldering competitions.

Experimental design

Prior to the investigation, participants were invited to an interview where they were informed verbally and in writing about the purpose, contents, and procedures of the study. To prevent pre-fatigue from adversely impacting bouldering performance, participants were advised to respect a rest period of 48 hours before the experiment, during which non-essential physical activities should be omitted. Upon arriving at the test centre, their personal characteristics and sport-specific backgrounds were assessed, and they participated in a pre-test to determine their sport-specific movement knowledge (see Data Collection Procedure section). After completing the pre-test, they undertook an individual warm-up of a standardised 20-minute duration.

In the subsequent stage of the experiment, participants were exposed to a 3.0-metre high and 30-degree overhanging spray wall with numerous climbing holds (see Figure 1). Three bouldering experts with elite bouldering skills ranging from 25–27 IRCRA points, extensive experience of 14+ years in bouldering, and coaching and routesetting qualifications at levels 4–6 of the European Qualifications Framework, defined a bouldering sequence of nine climbing movements and 10 handholds among these many holds. The holds of the boulder exhibited diverse sizes, shapes, and colours, thereby impeding participants from relying solely on visual cues to memorise the

Table 1. Personal characteristics and sport-specific backgrounds of the intermediate (INT), advanced (ADV), and elite (ELI) group.

	INT ($n = 20$)		ADV ($n = 20$)		ELI ($n = 20$)		Between-groups		
Variable (*unit*)	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F/H*	*p*	*r*
Age (*years*)	27.2	5^{a}	27.9	8^{a}	28.7	7^{a}	$H = 0.46$	.795	.095
Body weight (*kg*)	72.2	7^{b}	68.1	6^{a}	68.2	5^{b}	$H = 3.66$	.160	.295
Body height (*cm*)	179.1	6^{a}	178.6	5^{a}	178.8	5^{a}	$F = 0.05$	.951	.045
IRCRA (*score*[1])	16.2	$1^{\dagger d}$	22.2	$2^{\dagger d}$	25.8	$1^{\dagger d}$	$H = 51.09$	<.001	.953
Bouldering experience (*years*)	1.5	$1^{\dagger d}$	6.8	$5^{\dagger c}$	10.3	$5^{\dagger d}$	$H = 40.17$	<.001	.675
Bouldering competitions (*number*)	3.4	$3^{\dagger d}$	11.4	$7^{\dagger d}$	33.8	$20^{\dagger d}$	$H = 37.22$	<.001	.734

Note. Results are reported as $M \pm SD$. Statistical comparisons between two groups are presented using superscript characters, with the symbol † indicating significant differences ($p < .05$) between two consecutive groups and letters denoting the effect size *r* (^{a} $r < .1$; ^{b} $.1 \le r < .3$; ^{c} $.3 \le r < .5$; ^{d} $r \ge .5$). Between-group comparisons include either the ANOVA (*F*) or Kruskal-Wallis (*H*) results, the *p*-value, and the effect size *r*.

[1]International Rock Climbing Research Association's numerical scale of for classifying climbing skills (novice: ≤ 10 points; intermediate: 11–17 points; advanced: 18–23 points; elite: 24–27 points; world-class: ≥ 28 points).

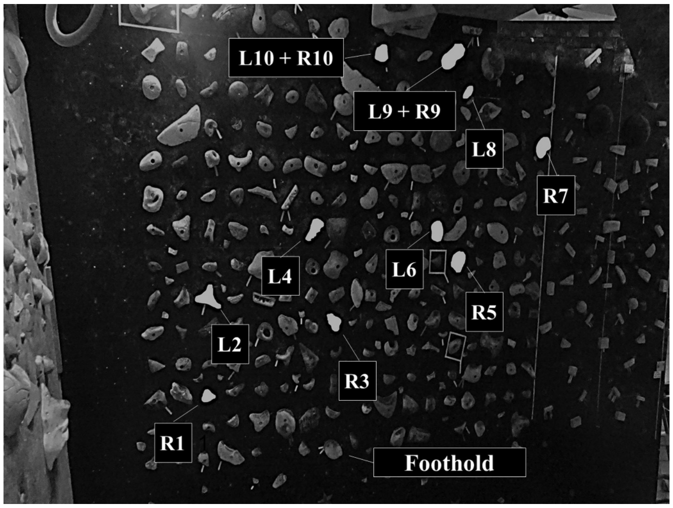

Figure 1. Boulder of the main experiment. *Note*. The figure shows the 3.0-m high and 30-degree overhanging spray wall that contained many climbing holds varying in size, shape, and colour. The holds used by the expert during the demonstration are numbered. The starting position consisted of the right hand on hold 1 (R1), the left hand on hold 2 (L2), and the right foot on the marked foothold. From there, the expert moved to hold 3 with the right hand (R3) and to hold 4 with the left hand (L4), then to hold 5 with the right (R5) hand and to hold 6 with the left hand (L6). He moved up to hold 7 with the right (R7) hand and grasped hold 8 (L8), and then hold 9 with the left hand (L9). He matched hold 9 with the right (R9) hand and grasped hold 10 first with the left hand (L10), and then with the right hand (R10). The participants were only allowed to place their feet on one of the numbered holds (foot-to-hand) plus the marked foothold for the starting position.

holds. The difficulty of the boulder was approximately 20 IRCRA points, classifying it as advanced and thus theoretically climbable for advanced and elite climbers; however, it extended the bouldering skills of intermediate participants.

Drawing on the observational learning framework, one of the experts made a practical demonstration of the boulder. That is, the experimental design offered an ecologically valid environment by including a realistic task and the observational learning methodology that climbers commonly encounter in bouldering. Participants were instructed to memorise the holds (i.e., these were not marked) and movements demonstrated by the expert. As is typically with spray walls, they were only allowed to use handholds as footholds (i.e., *foot-to-hand* principle), except for the marked starting foothold.

After the practical demonstration, participants received a standardised two-minute rehearsal period in compliance with IFSC rules for final rounds. Once they were familiar with the boulder, or at the latest when the two-minute time limit had elapsed, they were instructed to name the climbing holds belonging to the boulder by saying aloud and simultaneously indicating them with a stick. Likewise, they were asked to verbally describe the climbing movements demonstrated by the expert (e.g., *cross movement to hold 4 with the left hand*).

Following the recall task, participants were given a standardised four-minute ascent time to climb the boulder, again in accordance with IFSC rules. The experiment was terminated when participants reached the last hold of the boulder, or the four-minute bouldering time was up. After the climbing procedure, a post-experimental interview was conducted to assess details about the participants' recall strategies.

If participants failed to recall one or more holds after the rehearsal period, they verbally informed the experimental supervisor that they required a further demonstration of the holds. In this case, the bouldering expert who performed the practical demonstration repeated the holds belonging to the boulder from the start to the last hold using the stick. This process was iterated as often as required by participants until they memorised the holds of the boulder, allowing them to physically attempt the boulder. It is noteworthy that the expert did not perform any additional practical demonstrations, as these would have contributed to further observational learning processes.

Data collection procedure

Assessment of movement knowledge

Participants' sport-specific movement knowledge was assessed in a pre-test prior to the main experiment. To this end, participants were exposed to three boulders comprising different movements that climbers commonly encounter in modern bouldering (see Augste et al., 2021): an athletic boulder with dynamic and powerful climbing movements; a parkour-like boulder with running and jumping movements; and a tricky boulder with slow-paced and balancing movements. Participants were given a two-minute period to preview each boulder. Following each preview and without physically rehearsing the boulder, they were instructed to verbally describe the movement characteristics (e.g., *dynamic move to hold 3*) and the sequence of climbing movements (e.g., *grasp hold 2 with the left hand*) that they would execute when attempting it. The three bouldering experts (see Experimental Design section) independently rated how appropriately participants identified the movement characteristics and how accurately they described the sequence of movements using a 5-point Likert scale (1: poor; 2: fair; 3: good; 4: very good; 5: excellent). Likewise, participants had to self-estimate their sport-specific movement knowledge using the same 5-point Likert scale than the experts.

Assessment of memory abilities

In the main experiment, the three bouldering experts used video recordings to examine the number of climbing holds and movements successfully retained by the participants following the rehearsal period. Specifically, each expert independently determined the number of holds and movements participants were able to recall. The mean values of the three experts were retained as final scores. Moreover, considering that short rehearsal periods underline a prompt memorisation of climbing holds, participants' rehearsal times were recorded using a stopwatch. Additionally, the expert who performed the practical demonstration also documented the number of repetitions of the holds that participants required following the rehearsal period.

Assessment of bouldering performance

A successful completion of the boulder was retained when participants were able to climb the boulder from the starting holds to the finishing hold within the time limitation and using solely the holds of the practical demonstration. The assessment of whether they were able to climb the boulder was intended to examine whether participants possessed the motor and technical skills to integrate the perceived movement actions during the practical demonstration into a successful motor sequence.

Post-experimental interviews

Post-experimental interviews were implemented to assess details about the participants' memory strategies during the practical demonstration and rehearsal period. Initially, participants had to self-rate their memory performance during the practical demonstration using again the 5-point Likert scale. Moreover, they were requested to indicate (0 = *no*; 1 = *yes*) if they focused their attention during the practical demonstration solely on the holds, on the climbing movements performed by the expert, or on both. In this context, they also had to state (0 = *no*; 1 = *yes*) whether they used climbing hold cues, such as the identification of familiar brands or shapes, to memorise the boulder. Lastly, they were requested to indicate if they were able to mentally imagine themselves climbing the boulder and thereby performing embodied motor simulations during the rehearsal period (0 = *no*; 1 = *yes*).

Statistical analyses

Statistical analyses were conducted using IBM SPSS Statistics 29 (IBM Corporation, USA). Data are presented as mean values and standard deviations ($M \pm SD$). An alpha level of $p < .05$ (2-tailed) was used to determine statistical significance. A priori power analysis indicated a power (1-β) of .76, with an effect size $\eta^2 = .14$, based on a sample with 60 participants, three study groups, and an α of .05. The high effect size estimated in the power analysis is derived from previous research by Medernach & Memmert (Medernach et al., 2021), who observed high effects for study groups with similar sample sizes. An ANOVA (analysis of variance) was conducted to determine differences of the means between the study groups. All variables were assessed for normality of distribution using the one-sample Kolmogorov-Smirnov test. Levene's test was used to verify the homogeneity of variance, and Bonferroni post-hoc pairwise comparisons were calculated to determine between-group differences. The non-parametric Kruskal-Wallis one-way analysis of variance and the Mann-Whitney test were used when ANOVA assumptions were violated. The Eta-square was calculated and converted into r to indicate the effect sizes between the groups. Besides categorising climbing skill into ability groups, separate linear regressions were conducted to examine the effect of dependent variables (e.g., movement knowledge) on predictor variables (e.g., recalled holds). The Spearman's rank-order correlation coefficient was used to determine a significant relation between two variables.

Results

Movement knowledge

With regard to the pre-test assessing the participants' sport-specific movement knowledge, the intra-class correlation coefficient revealed a high level of consistency among the three bouldering experts (movement characteristics: $r = .949$, $r = .915$, $r = .969$; climbing movements: $r = .897$, $r = .869$, $r = .912$), thereby confirming a strong inter-rater reliability. In this context, the intra-class correlation coefficient also indicated a high consistency ($r = .854$) between the averaged movement knowledge ratings of the three experts and the participants' self-ratings of their movement knowledge.

Participants from the ELI group (4.6 ± 0.3) attained higher movement knowledge scores compared to participants from the ADV (2.8 ± 0.6, $p < .001$, $r = .885$) and INT (1.8 ± 0.4, $p < .001$, $r = .970$) group, with $F(2, 59) = 177.34$, $p < .001$, $r = .928$. Furthermore, linear regression analysis indicated a positive effect between the participants' movement knowledge (dependent variable) and the following predictor variables: (a) their IRCRA scores, with $F(1, 59) = 138.5$, $p < .001$, $R^2 = .705$, $b = 0.25$, 95% CI: [0.21, 0.29]; (b) their bouldering experience in years, with $F(1, 59) = 52.71$, $p < .001$, $R^2 = .476$, $b = 0.16$, 95% CI: [0.12, 0.20]; and (c) their number of bouldering competitions, with $F(1, 59) = 45.14$, $p < .001$, $R^2 = .44$, $b = 0.05$, 95% CI: [0.03, 0.06].

Memory abilities

The ANOVA indicated that participants from the INT group recalled a lower number of climbing holds (3.9 ± 0.8) than participants from the ADV (6.5 ± 1.5) and ELI (7.1 ± 1.7) group (see Table 2). Linear regression analysis revealed a positive effect between the participants' number of recalled climbing holds (dependent variable) and both, their IRCRA scores, with $F(1, 59) = 54.33$, $p < .001$, $R^2 = .484$, $b = 0.33$, 95% CI: [0.24, 0.42]; and their movement knowledge, with $F(1, 59) = 37.61$, $p < .001$, $R^2 = .393$, $b = 0.99$, 95% CI: [0.67, 1.32]. The intra-class

Table 2. Memory abilities of the intermediate (INT), advanced (ADV), and elite (ELI) group.

	INT ($n = 20$)		ADV ($n = 20$)		ELI ($n = 20$)		Between-groups		
Variable (*unit*)	M	SD	M	SD	M	SD	F /H	p	r
Recalled holds (*number*)	3.9	$0.8^{†d}$	6.5	1.5^{b}	7.1	$1.7^{†d}$	$F = 28.47$	<.001	.707
Recalled movements (*number*)	3.5	$1.1^{†d}$	6.1	$0.8^{†d}$	7.9	$0.3^{†d}$	$F = 142.2$	<.001	.913
Self-assessed memory abilities (*score*[1])	1.8	$0.6^{†d}$	3.7	$0.9^{†c}$	4.4	$0.8^{†d}$	$H = 40.52$	<.001	.832
Rehearsal times (*seconds*)	106.5	$14.9^{†c}$	85.4	$26.4^{†d}$	43.5	$14.9^{†d}$	$F = 54.14$	<.001	.809
Repetition of the holds (*number*[2])	3.0	$1.1^{†d}$	1.6	0.7^{c}	0.9	$0.4^{†d}$	$F = 37.36$	<.001	.753

Note. Results are reported as $M \pm SD$. Statistical comparisons between two groups are presented using superscript characters, with the symbol † indicating significant differences ($p < .05$) between two consecutive groups and letters denoting the effect size r (^{a} $r < .1$; ^{b} $.1 \le r < .3$; ^{c} $.3 \le r < .5$; ^{d} $r \ge .5$). Between-group comparisons include either the ANOVA (F) or Kruskal-Wallis (H) results, the p-value, and the effect size r.

[1]Self-perceived using a 5-point Likert scale (i.e., 1: *not appropriate*; 2: *somewhat appropriate*; 3: *appropriate*; 4: *very appropriate*; 5: *best possible*).

[2]Indicates the number of repetitions of the climbing holds participants required following the initial recall task before they were able to memorise the bouldering sequence.

correlation coefficient revealed perfect consistency ($r = 1$) among the three experts regarding the number of recalled climbing holds.

Furthermore, the ANOVA results also indicated that the ELI group demonstrated a more accurate recall of the climbing movements (7.9 ± 0.3) than the ADV (6.1 ± 0.8) and INT (3.5 ± 1.1) group (see Table 2). Linear regression analysis revealed a positive effect between the participants' number of recalled climbing movements (dependent variable) and both, their IRCRA scores, with $F(1, 59) = 178.38$, $p < .001$, $R^2 = .755$, $b = 0.41$, 95% CI: [0.35, 0.48]; and their movement knowledge, with $F(1, 59) = 113.18$, $p < .001$, $R^2 = .661$, $b = 1.30$, 95% CI: [1.06, 1.55]. The intra-class correlation coefficient revealed perfect consistency ($r = 1$) among the three experts regarding the number of recalled climbing movements.

The ELI group exhibited shorter rehearsal times (43.5 ± 14.9 s) following the practical demonstration than the ADV (85.4 ± 26.4 s) and INT (106.5 ± 14.9 s) group (see Table 2). Following the rehearsal period, participants from the INT group required more repetitions of the holds before they were able to memorise the boulder (3.0 ± 1.1) than participants from the ADV (1.6 ± 0.7) and ELI (0.9 ± 0.4) group.

Bouldering performance

Following the rehearsal period, all participants from the ADV and the ELI (1.0 ± 0.0) group succeeded in climbing the boulder. In contrast, only two participants from the INT group (0.10 ± 0.3, $p < .001$, $r = .900$) were able to climb the boulder. The intra-class correlation coefficient indicated perfect consistency ($r = 1$) among the experts for the number of completed boulders.

Reports from the post-experimental interviews

The ELI group reported higher self-perceived memory abilities during the practical demonstration (4.4 ± 0.8) than the ADV (3.7 ± 0.9) and INT (1.8 ± 0.6) group (see Table 2). Participants from the INT group stated more often to have focused during the practical demonstration on the climbing holds (0.75 ± 0.44) than participants from the ADV (0.20 ± 0.41, $p < .001$, $r = .543$) and ELI (0.10 ± 0.31, $p < .001$, $r = .649$) group, with $H(2) = 21.18$, $p < .001$, $r = .599$, and non-significant differences between the latter ones ($p = .602$; $r = .136$). The majority of the participants from the INT (0.15 ± 0.37), ADV (0.10 ± 0.31), and ELI (0.05 ± 0.24) group disagreed that they had focused exclusively on the climbing movements performed by the expert, with $H(2) = 1.09$, $p = .579$, $r = .139$. In contrast, the ELI (0.85 ± 0.37, $p < .001$, $r = .740$) and ADV (0.70 ± 0.47, $p < .001$, $r = .602$) group indicated more often to have focused on both, the holds and movements than the INT group (0.10 ± 0.31), with non-significant differences between the latter ones ($p = .677$, $r = .175$).

The ELI group (0.90 ± 0.31) reported having relied more often on climbing hold cues to memorise the boulder than the ADV (0.50 ± 0.51, $p = .006$, $r = .428$) and INT group (0.20 ± 0.41, $p < .001$, $r = .694$), with $H(2) = 19.49$, $p < .001$, $r = .574$. In addition, intermediate climbers (0.15 ± 0.37) reported less often that they were able to mentally visualise themselves climbing the boulder (performing motor simulations) during the rehearsal period than advanced (0.90 ± 0.31, $p < .001$, $r = .740$) and elite (1.0 ± 0.0, $p < .001$; $r = .852$) climbers, with non-significant differences between the latter ones ($p = .771$, $r = .222$). Linear regression analysis revealed a positive effect between the participants' ability to mentally visualise the movements (dependent variable) and the following predictor variables: (a) number of recalled climbing holds, with $F(1, 59) = 21.84$, $p < .001$, $R^2 = .274$, $b = 0.13$, 95% CI: [0.07, 0.19]; (b) number of recalled movements, with $F(1, 59) = 64.59$, $p < .001$, $R^2 = .527$, $b = 0.17$, 95% CI: [0.13, 0.21]; and the participants' movement knowledge scores, with $F(1, 59) = 35.67$, $p < .001$, $R^2 = .381$, $b = 0.23$, 95% CI: [0.15, 0.31].

Discussion

The purpose of this study was to extend previous research on memory in sport climbing (Boschker et al., 2002; Pezzulo et al., 2010) and bouldering (Whitaker et al., 2019) by investigating the relation between bouldering proficiency and domain-specific visual memory abilities. We examined the ability of climbers of different skill levels to memorise the holds and movements of a bouldering sequence set up on a spray wall and demonstrated by a bouldering expert. Findings revealed a positive effect between the climbers' IRCRA scores and the number of holds and movements they were able to recall after a two-minute rehearsal period. Moreover, elite climbers demonstrated a more accurate recall of the climbing movements than advanced and intermediate climbers. These findings indicate that bouldering expertise is positively associated with the ability to memorise domain-specific information and thus confirm our hypothesis 1. Higher self-perceived memory abilities during the practical demonstration and shorter rehearsal times after the practical demonstration among the ELI group, as well as more repetitions of the climbing holds requested by the INT group to memorise the boulder, provide further support for our hypothesis that bouldering expertise is linked to perceptual-cognitive memory skills.

Although the memory paradigm in our experiment included additional memory constraints (i.e., practical demonstration, spray wall with many unmarked holds) that risked having affected the outcomes (Roca & Williams, 2016) by disadvantaging inexperienced climbers, our findings are consistent with superior memory abilities observed by Whitaker et al., (2019) in expert climbers following a one-minute route previewing and after attempting three boulders of their choice. Furthermore, the results of our study are also consistent with other sports domains, such as chess (e.g., Connors et al., 2011), soccer (e.g., Zoudji et al., 2010), or action video games (e.g., Green & Bavelier, 2003), revealing that the ability to memorise sport-specific task information is associated with expertise and domain-specific search skills.

A key aim of this study was to elucidate potential mechanisms that could explain superior memory abilities among skilled climbers in the modality of bouldering. In our experiment, only two intermediate climbers were able to climb the boulder. This finding supports the advanced difficulty level of the boulder proposed by the three experts, and indicates that the boulder was beyond the ability of intermediate climbers. Considering that intermediate climbers did not possess the motor and technical skills to climb the boulder, it is likely that they were overwhelmed with processing visual sensory input during the practical demonstration. Longer rehearsal times (i.e., the mean value in Table 2 indicates that intermediate climbers were close to the cut-off time), and more repetitions of the climbing holds subsequent to the rehearsal period among intermediate climbers support this assumption. Additionally, intermediate climbers indicated in the post-experimental interviews less often that they were able to mentally visualise themselves climbing the boulder than their more experienced counterparts. In line with Pezzulo et al., (2010), these results emphasise that limited motor and technical skills appear to have impeded intermediate climbers from performing embodied motor simulations. This may have obligated them to mainly rely on a purely visual inspection of structural features, such as the size and orientation of climbing holds, which, in agreement with Boschker et al., (2002), may have had a negative impact on their memory abilities. This is because a purely visual processing of climbing holds risked having exceeded their short-term memory capacity (Sala & Gobet, 2017). Although our experiment included only one boulder, which may not provide enough evidence to make general conclusions about memory in bouldering, our findings provide support for hypothesis 2 and suggest that climbers' ability to remember boulder features is related to its feasibility and, therefore, associated with climbers' bouldering proficiency.

When discussing the superior memory abilities we observed among skilled climbers, it is critical to take into account their movement knowledge. Besides superior movement knowledge scores among elite climbers, a major outcome of our study was the positive relation between the participants' movement knowledge and their ability to recall the holds and movements. Extending the research conducted by Whitaker et al. (2019), these results suggest that possessing a profound knowledge of climbing movements had a positive impact on the participants' memory, supporting hypothesis 3 that memory in bouldering is associated with domain-specific movement knowledge.

Building on the work by Cowell et al., (2019) and Sala and Gobet (2017), it is likely that a profound movement knowledge enabled experienced climbers to identify familiar climbing movement patterns during the practical demonstration. To illustrate, in our experiment, the expert began his demonstration in a cross movement position, with the right hand on the R1 hold and the left hand on the L2 hold (see Figure 1). Recognising the cross movement position was reliant on the climbers' movement knowledge and thus could have helped skilled climbers in memorising the holds of the start more effectively. This is because a cross movement typically necessitates a particular arrangement of climbing holds, which limited the options of holds belonging to the boulder and thus simplified memorisation through selection process. As such, skilled climbers' movement knowledge may have helped them in clustering visual perceptual stimuli into a bouldering choreography. An interesting finding supporting this assumption is that elite climbers reported more often having relied on cues from the climbing holds to memorise the boulder. While this finding somewhat contradicts the study by Boschker et al. (2000), who proposed that skilled climbers pay less attention to structural features, it supports hypothesis 3 that experienced climbers have an advantage through their movement knowledge when it comes to recognising familiar climbing holds, which serve as cues accessing chunks. However, further research is needed to improve understanding of how climbers rely on cues to memorise boulder features, as spray walls per se necessitate climbers to focus more on hold features than conventional boulders due to the numerous climbing holds.

The superior movement repertoire of skilled climbers is also likely to explain the distinct memory strategies applied by the study groups, with advanced and elite climbers having focused more on both, the holds and movements and thus on functional aspects of the boulder, while intermediate climbers reported to have mostly focused solely on the holds. Our findings suggest that intermediate climbers predominantly relied on memorising individual holds, whereas advanced and elite climbers aimed to elaborate motor chunks comprising a series of climbing holds coupled with action. Although this assumption draws on self-reports, which should be interpreted with caution (e.g., binary yes/no answers may have artificially inflated significant between-group differences), it is likely, in line with Boschker et al., (2002) and Pezzulo et al., (2010), that this allowed skilled climbers to process a larger amount of sensory information during the demonstration, while a purely visual memorisation of structural features overwhelmed intermediate climbers in memorising the boulder.

Conclusion

Memory plays a critical role in bouldering, as it allows climbers to develop appropriate climbing strategies, to mentally rehearse climbing movements, and to recall the climbing holds of boulders. Consistent with previous research, the results of this study provide evidence that bouldering expertise is associated with the perceptual-cognitive ability to memorise and recall climbing holds and movements. Our findings suggest that memory in bouldering is associated with the feasibility of the boulder and domain-specific movement knowledge, coupled with better mental visualisation and increased attentional focus on functional aspects of boulders. In particular, the extensive movement knowledge of skilled climbers appears to enable them to process sensory input more effectively, to compare perceived stimuli with patterns stored in long-term memory, and to recognise familiar climbing movement patterns. This helps them to cluster perceptual stimuli into motor chunks comprising a series of climbing holds associated with action, increasing short-term storage capacity and speed of information processing.

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