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The Climbing Movement Repertoire in Olympic Bouldering: Exploring Its Role in Decision-Making, Performance, and Time Constraint Management

Jerry Prosper Medernach [a,b], Julian Henz [a], Daniel Memmert [a], and Xavier Sanchez [c,d]

[a]German Sport University Cologne; [b]University of Luxembourg; [c]Université d'Orléans; [d]Université Paris-Saclay

ABSTRACT
In Olympic bouldering, climbers must solve a series of boulders, which are short routes set on low-height climbing walls. Time constraints imposed by competition regulations limit the time available for strategic decisions and climbing attempts. An extensive climbing movement repertoire helps climbers to identify meaningful movement patterns and anticipate climbing solutions. Expert routesetters—those climbers responsible for setting boulders—have been described to possess an extensive climbing movement repertoire. This study explored the role of the movement repertoire as an underlying cognitive system in decision-making, climbing performance, and time constraint management in Olympic bouldering. A total of 48 elite climbers—including 24 climbers with professional routesetting expertise (RS) and 24 climbers without any routesetting expertise (NR)—were tasked with climbing two boulders under varying time constraints (B1: four minutes; B2: two minutes). Data collected included non-stored climbing movements, strategic decision-making, and performance-related variables. In both boulders, the RS group had fewer non-stored climbing movements, showed enhanced decision-making skills (shorter previewing times, more effective climbing solutions, fewer strategic adjustments), and achieved better climbing performances (higher top rates, fewer attempts, higher holds in best attempts). Furthermore, in B2, the RS group was less perturbed by increased time constraints, showing a smaller decline in non-stored climbing movements, strategic decision-making, and climbing performance compared to the NR group. Routesetting expertise appears to be a relevant performance parameter in climbing. Climbers with such expertise benefit from their extensive movement repertoire to make efficient decisions, optimize performance, and effectively manage time constraints.

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Over the past two decades, the sport of Olympic bouldering has evolved from a recreational and outdoor activity into a fully acknowledged competitive climbing discipline (Henz et al., 2025; Medernach & Memmert, 2021). The increasing competitiveness of Olympic bouldering has also sparked research interest in exploring factors underlying expert climbers' performances. In this endeavor, previous research has primarily addressed physical aspects critical to achieving optimal bouldering performances, such as finger strength and muscular endurance (e.g., Fanchini et al., 2013; Medernach et al., 2015; Stien et al., 2019). In recent years, however, research has also begun to explore the role of perceptual-cognitive factors as key determinants of success in bouldering. This research has revealed that expert climbers possess superior decision-making skills (Medernach et al., 2021), demonstrate greater accuracy in estimating their motor capabilities (Whitaker et al., 2019), benefit from enhanced cognitive-behavioral skills during route previewing (Medernach, Sanchez, et al., 2024), are better in identifying creative climbing solutions (Künzell et al., 2021), and are characterized by higher strategic planning skills (Medernach, Henz, Memmert, & Sanchez, 2024).

The critical role of climbers' perceptual and cognitive skills in Olympic bouldering is inherently associated with the characteristics and competition regulations of the sport (see Hatch & Leonardon, 2024). Bouldering competitions involve a series of boulders, which are short climbing routes set on low-height climbing walls. A major challenge is that competitors must solve these strenuous, complex, and creative climbing movements within a time limit of four to five minutes. While climbers can make multiple attempts within the allotted time for each boulder, the number of attempts needed to complete a boulder is considered in their competition ranking. Therefore, athletes must make appropriate decisions and develop efficient climbing solutions to solve these boulders in as few attempts as possible (Medernach, Henz, Memmert, & Sanchez, 2024).

Recent research has elucidated the pivotal role of route previewing in identifying efficient climbing solutions and making optimal decisions (Medernach, Sanchez, et al., 2024; Sanchez et al., 2019). Route previewing refers to the perceptual-cognitive process of analyzing and interpreting climbing movements before actually attempting them (Sanchez et al., 2012). This process involves visually scanning climbing movements and gathering functional information from visual cues of climbing holds, which helps climbers to plan their ascents and develop potential climbing solutions (Medernach, Sanchez, et al., 2024).

Beyond identifying effective climbing strategies during route previewing, a further perceptual-cognitive skill of

CONTACT Jerry Prosper Medernach research@climbing.science Institute of Exercise Training and Sport Informatics, German Sport University Cologne, Am Sportpark Müngersdorf 6, Cologne 50933, Germany.
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climbers includes effectively managing time during climbing (Mckellar et al., 2023). The critical relevance of effective time management arises from the fact that, although each boulder consists of only a maximum of 12 climbing holds, time constraints restrict the number of attempts climbers can make (Augste et al., 2021). Indeed, research has shown that, as a consequence of these time constraints imposed by competition regulations, world-class competitors typically make an average of only three to five attempts on each boulder (Mckellar et al., 2023; Medernach et al., 2016). Such time constraints become particularly critical when climbers misinterpret the movements of boulders, potentially leading to poor decision-making and ineffective climbing solutions (Medernach, Henz, Memmert, & Sanchez, 2024). This typically occurs when climbers encounter unfamiliar climbing movements that are not yet stored in their movement repertoire (Henz et al., 2025; Medernach, Henz, & Memmert, 2024).

The climbing movement repertoire is a cognitive system that has only recently garnered research attention in Olympic bouldering. In consideration of the time constraints inherent to Olympic bouldering, elucidating its role in making effective decisions despite time limitations could offer valuable insights for competitors and coaches. In short, the movement repertoire paradigm posits that experts rely on those climbing movements stored in their long-term memory to interpret visual sensory input, recognize meaningful movement patterns, and anticipate climbing movements (Henz et al., 2025; Medernach, Henz, & Memmert, 2024). These high-level knowledge structures, developed through long-term expertise and deliberate practice, enable climbers to efficiently interpret climbing movements processed in working memory by comparing them with movement patterns stored in long-term memory. The higher this cognitive-motor knowledge acquired through domain-specific expertise (Mangan et al., 2024), the better climbers can identify potential climbing solutions based on the arrangement of climbing holds (Medernach et al., 2025). Building on the Adaptive Control of Thought (ACT) theory by Anderson (1983), the movement repertoire encompasses declarative knowledge ("knowing what"), derived from a semantic network, which enables climbers to determine the appropriate action (e.g., executing a dynamic movement) when faced with a specific arrangement of climbing holds. Consequently, a broad movement repertoire enhances climbers' awareness of potential movements and solutions when encountering climbing routes or boulders.

While research has only recently begun to empirically examine the role of the movement repertoire in achieving optimal climbing performance, the first study to identify the pivotal role of such a repertoire was conducted by Ferrand et al. (2006) nearly two decades ago. The authors explored potential impediments to successful climbing performance as perceived by elite competitors, who identified a lack of climbing route knowledge as a major self-handicap in climbing competitions. Later, Sanchez et al. (2019) surveyed expert climbing coaches, who described an extensive, domain-specific movement repertoire as one of the critical factors for success in sport climbing. More recently, Medernach, Henz, Memmert, and Sanchez (2024) described a broad repertoire of climbing movements as a pivotal factor contributing to optimal strategic planning of Olympic boulders.

In numerous sporting activities, motor actions require the integration of perceptual information processed in short-term memory with movement patterns stored in long-term memory (Cowell et al., 2019; Roca & Williams, 2016). That is, domain-specific movement knowledge is essential for interpreting sensory input, decoding task-specific movement patterns, and quickly accessing retrieval structures in long-term memory (Cowan, 2008; Sala & Gobet, 2017). The concept of different memory storage systems originates from Atkinson and Shiffrin (1968), who proposed a structural multistore model with three classifications: sensory memory, short-term memory, and long-term memory. Despite varying theoretical frameworks, short-term memory can be understood as a multi-component workspace, where sensory input is consciously processed and associated with knowledge retrieved from long-term memory (Adams et al., 2018; Cowan, 2008). Short-term memory is limited in both storage capacity and duration, and processed information must be encoded to enter long-term memory, where it can be stored for extended periods (Camina & Güell, 2017; Cowan, 2008).

In their seminal work on skill in chess, Chase and Simon (1973) replicated De Groot's (1956) foundational experiment on the relationship between chess expertise and players' ability to recall chess positions. The authors observed that the perceptual-cognitive ability to recall meaningful chess positions was associated with the recognition of familiar chess patterns stored in long-term memory, highlighting that the acquisition of high-level knowledge structures positively affects short-term memory and recall capacity (Hambrick & Meinz, 2011; Sala & Gobet, 2017). Similarly, Chase and Ericsson's (1982) skilled memory theory posits that superior working memory capacities of skilled individuals are related to their ability to quickly retrieve domain-specific knowledge stored in long-term memory. Later, Ericsson and Kintsch (1995) proposed that experts rely on their long-term memory as an extension of short-term memory, thereby assuming that a large repertoire of patterns in long-term memory enhances both storage capacity and speed of information processing of short-term memory.

While these seminal works emphasize the pivotal role of movement patterns and domain-specific high-level knowledge stored in long-term memory, research has yet to further explore the role of the movement repertoire as a cognitive system in Olympic bouldering. In particular, less is known whether an extensive repertoire of climbing movements could serve as an underlying system that helps climbers to manage time constraints and make appropriate decisions despite imposed time limitations. Yet, a major challenge in this context is to explore climbers' movement repertoire in situ and under ecologically valid conditions. That is, climbing conditions that adhere to IFSC (International Federation of Sport Climbing) regulations, with boulders reflecting the naturality and complexity of movements that experts encounter in bouldering (Holleman et al., 2020).

A methodological approach to indirectly investigate the critical role of climbers' movement repertoire under such conditions is to examine decision-making, climbing performance, and time constraint management of experts who possess an extensive repertoire of climbing movements. Expert routesetters—those climbers who are responsible for designing and setting boulders—have recently been described to possess such an extensive climbing movement repertoire (Henz et al., 2024). In fact, these experts draw on their vast repertoire of climbing movements to set and design versatile climbing movements that challenge even the most proficient climbers to their limits. Their repertoire arises not only from long-term climbing expertise, but also from their routesetting practices, where they are required to design versatile and innovative boulders for climbers of all ability levels.

The purpose of this study was to explore the role of the climbing movement repertoire as an underlying cognitive system in decision-making, climbing performance, and time constraint management in Olympic bouldering. To this end, elite climbers—including climbers with routesetting expertise and climbers without such routesetting expertise—were tasked with climbing two boulders under varying time constraints: four minutes for the first boulder (B1) and two minutes for the second boulder (B2). This methodological approach enabled a comparison of decision-making, climbing performance, and time management under varying time constraints between expert climbers with similar climbing backgrounds, differing mainly in their routesetting expertise.

Consistent with the movement repertoire paradigm (Medernach, Henz, & Memmert, 2024), we hypothesized (Hypothesis 1: IFSC condition effect) that in the B1 boulder, climbers with routesetting expertise (RS) would demonstrate superior decision-making and better climbing performances compared to climbers without routesetting experience (NR). This is because a superior movement repertoire, developed through additional routesetting expertise, enables them to more accurately process sensory input and more effectively understand climbing movements. Building on this first hypothesis, we furthermore hypothesized (Hypothesis 2: time constraints effect) that in the B2 boulder, the RS group would not only outperform the NR group, but would also demonstrate a smaller decline in decision-making and climbing performances, thereby indicating superior time constraint management. This is because a more extensive climbing movement repertoire helps them to more quickly process sensory input and anticipate climbing movements.

Materials and methods

Participants

A total of 48 elite climbers—including 24 climbers with professional routesetting expertise (RS group) and 24 climbers without any routesetting expertise (NR group)—voluntarily participated in this study (see Table 1). Considering the resource constraint in attaining a maximal sample size of professional routesetters with elite climbing levels, the sample size in the present study is justified by recent research on strategic planning in Olympic bouldering, which used similar data collection procedures and reported substantial effect sizes despite smaller sample sizes ($\eta^2 \geq .27$; see Medernach, Henz, Memmert, & Sanchez, 2024). Furthermore, the number of participants involved in the present study contributed to two study groups with equal sample sizes.

Participants were at least 18 years old, in good health, and had no recent injuries that could have affected their climbing performance during the study. All participants provided written informed consent and were given both verbal and written explanations regarding the study's purpose and procedures. The study adhered to the World Medical Association guidelines and received ethical approval from the University Ethics Committee (ID 229/2023).

No significant differences were found between the RS and NR groups in personal characteristics, with Wilk's Lambda $\Lambda = 0.928$, $F(3, 44) = 1.140$, $p = .343$, $\eta^2 = .072$. Specifically, both groups had similar ages, body heights, and weights (see Table 1). Likewise, no significant differences were found between the groups in climbing levels, years of climbing experience, competitive expertise, technical skills, and grip strength, with Wilk's-Lambda $\Lambda = 0.906$, $F(6, 41) = 0.711$, $p = .642$, $\eta^2 = .094$. Both groups had more than 10 years of climbing experience and elite climbing levels, with an average of 24 points (level 4) on the IRCRA (International Rock Climbing Research Association) scale. The only climbing-related variable that revealed a significant difference between the two groups was the participants' routesetting experience; the RS group had an average of 10 years of professional routesetting expertise, while the NR group did not have any such expertise (see Table 1).

Table 1. Personal characteristics and climbing expertise of the routesetter (RS) and non-routesetter (NR) groups.

Variable (unit)	RS (n = 24)	Min	Max	NR (n = 24)	Min	Max
Age (*years*)	29.4 (26.0/28.5/32.8)	20	41	27.6 (23.0/25.0/35.0)	18	43
Weight (*kg*)	70.8 (67.3/70.0/77.3)	53	83	72.2 (62.8/72.0/80.0)	53	91
Height (*cm*)	177.2 (174.0/178.0/180.8)	163	193	179.8 (175.3/179.5/182.0)	169	194
Current climbing level (*IRCRA score*)	23.7 (22.0/24.0/25.0)	21	28	23.7 (22.0/23.0/25.0)	22	27
Highest climbing level (*IRCRA score*)	24.9 (23.3/25.0/26.0)	22	30	24.7 (23.0/24.0/26.0)	23	28
Climbing experience (*years*)	12.8 (7.3/12.0/17.0)	7	22	11.8 (9.0/10.5/15.0)	6	19
Competitive experience (*years*)	5.4 (4.0/5.0/7.0)	2	10	4.8 (2.3/5.0/6.8)	1	10
Technical climbing skills (*score*)	3.5 (3.0/3.5/4.0)	3	4	3.5 (3.0/3.0/4.0)	3	5
Grip strength (*kg*)	60.4 (57.0/62.0/64.8)	37	71	62.9 (54.5/63.5/71.0)	47	79
Routesetting experience (*years*)	10.0 (6.0/9.5/14.0)	5	18	/	/	/

Note. Results are presented as means (*M*), followed by the 25^{th}, 50^{th}, and 75^{th} percentiles in brackets, along with the minimum (*Min*) and maximum (*Max*) values.

Given that physical states and general well-being can influence performance in sporting activities (e.g., Saw et al., 2016), participants' physical states prior to the start of the climbing procedure were assessed to explore potential factors that could influence between-group comparisons (see Measures section). Findings revealed significant differences between the two groups, with Wilk's-Lambda $\Lambda = 0.799$, $F(4, 43) = 2.697$, $p = .043$, $\eta^2 = .201$. More precisely, the NR group had higher health (4.0 ± 0.3, $z = -2.17$, $p = .030$, $r = .314$) and training scores (4.0 ± 0.3, $z = -2.40$, $p = .016$, $r = .347$) than the RS group (health: 3.8 ± 0.3; training: 3.8 ± 0.3), while both groups reported similar activation (3.9 ± 0.3, 4.1 ± 0.4, $z = -1.14$, $p = .253$, $r = .165$) and flexibility scores (4.0 ± 0.6, 3.9 ± 0.3, $t = -0.48$, $p = .632$, $r = .071$).

Similarly, given that psychological states prior to climbing can be a critical factor in determining climbing success (e.g., Sanchez et al., 2010), participants' psychological states before climbing each boulder were assessed. Findings revealed no significant differences between the groups for the B1 boulder, with Wilk's-Lambda $\Lambda = 0.946$, $F(3, 44) = 0.829$, $p = .485$, $\eta^2 = .054$, and the B2 boulder, with Wilk's-Lambda $\Lambda = 0.953$, $F(3, 44) = 0.723$, $p = .544$, $\eta^2 = .047$. In addition, participants in the RS group had comparable psychological states before climbing the B1 boulder (cognitive anxiety: 4.2 ± 2.0, somatic anxiety: 5.7 ± 2.4, self-confidence: 4.0 ± 2.4) and the B2 boulder (cognitive anxiety: 4.1 ± 2.3, somatic anxiety: 5.0 ± 2.5, self-confidence: 4.2 ± 2.2), with Wilk's-Lambda $\Lambda = 0.860$, $F(2, 22) = 1.791$, $p = .190$, $\eta^2 = .140$. Similar findings were observed for the NR group before climbing the B1 boulder (cognitive anxiety: 4.6 ± 2.0, somatic anxiety: 5.5 ± 1.8, self-confidence: 4.8 ± 2.2) and the B2 boulder (cognitive anxiety: 4.8 ± 2.2, somatic anxiety: 5.7 ± 2.3, self-confidence: 4.9 ± 1.9), with Wilk's-Lambda $\Lambda = 0.999$, $F(2, 22) = 0.006$, $p = .994$, $\eta^2 = .001$.

Overview of the experimental design

Prior to the experimental testing, participants were required to sign the consent form and complete a questionnaire designed to assess their climbing expertise. In the following step, they engaged in their routine warm-up programs to ensure optimal physiological and psychological preparation. Once they indicated that they were sufficiently warmed up and mentally ready, their body characteristics, grip strength, and pre-performance physical states were assessed.

Following the completion of these preliminary test procedures, participants were successively exposed to the two boulders of the study. Before attempting each boulder, their psychological states were assessed (cognitive anxiety, somatic anxiety, self-confidence). In accordance with the IFSC regulations, they had to climb both boulders in a predefined sequence, starting with the B1 boulder and then proceeding to the B2 boulder. Between both boulders, participants were given, in line with the IFSC rules, a standardized four-minute rest. Participants were not allowed to view the boulders before the beginning of the experiment. In addition, they were tested individually to avoid any exchange of information and ensure they did not observe other participants during their attempts.

For both boulders, participants were given specific time limitations: four minutes for the B1 boulder and two minutes for the B2 boulder. The rationale for these time limitations was twofold: firstly, the four-minute limit for B1 aligns with IFSC rules, ensuring "real-world" conditions; secondly, research in Olympic bouldering has revealed that expert climbers' attempt durations typically range from 15 to 30 seconds (Mckellar et al., 2023; Medernach et al., 2016; White & Olsen, 2010). Therefore, the two-minute limit considerably increased time constraints, while still providing participants with enough time to complete the boulder. For both boulders, the climbing procedure ended under one of three scenarios: either when participants successfully completed the boulder, when the time

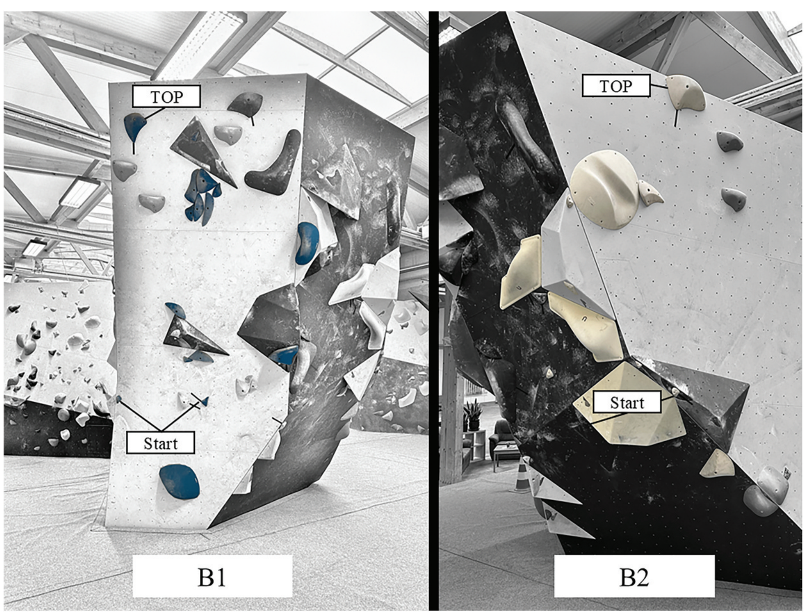

Figure 1. The two boulders of the study.

limit was reached, or when they decided not to make any further attempts.

Design of the boulders

Two professional routesetters, each with over 20 years of climbing experience, routesetting qualifications (i.e., European Qualifications Framework: ≥ level 3), and elite climbing levels (i.e., ≥ 25 IRCRA points), were assigned the task of setting the two boulders (see Figure 1). Both boulders were newly set to ensure that participants were not familiar with the climbing movements before data collection.

To enable valid and reliable comparisons, both boulders included a similar number of climbing movements, had equal difficulty levels, and involved similar movement demands. Specifically, both expert routesetters, responsible for designing the boulders, assigned a difficulty level of 20 IRCRA points to each boulder. This means that the two boulders were theoretically climbable by both groups. Furthermore, in accordance with the climbing movement classification proposed by Medernach, Henz, Memmert, and Sanchez (2024), the two boulders were classified within the *athletic* category, predominantly characterized by strenuous and powerful movements.

Measures

Personal characteristics

The participants' body weight and height were assessed before the climbing procedure (see Table 1). Body weight was measured in shorts and t-shirts to the nearest 0.1 kg using a digital scale (Breuer GS435B). Body height was determined without shoes to the nearest 0.5 cm using a stadiometer (Seca 213).

Climbing expertise

The participants' climbing levels were assessed using the IRCRA scale. This widely accepted scale converts climbing grades into a numerical system and is considered a reliable and valid tool for classifying climbing levels (see Draper et al., 2016). Climbing levels included both the most difficult boulder participants managed to climb "redpoint" (i.e., after practicing a boulder) at the time of the study (i.e., "*What is your current highest bouldering grade you can climb?*") and their highest levels ever climbed (i.e., "*What was your highest bouldering level?*").

In addition, their overall technical climbing skills (i.e., "*Rate your overall level of technical climbing proficiency on the following scale*") were assessed through self-reports using a 5-point Likert scale (1: poor, 2: moderate, 3: good, 4: very good, 5: excellent). Grip strength was measured using a calibrated hand dynamometer (Smedley Spring Type) and by implementing a sport-specific test protocol (see Medernach et al., 2015). Participants completed three repetitions with their dominant hand, by gradually applying maximum pressure for two seconds. The highest score achieved was recorded, with a standardized one-minute rest period between consecutive trials.

Physical states

Participants' physical states prior to data collection were assessed using Kleinert's (2006) PEPS (Perceived Physical State) questionnaire. This reliable and valid 20-item questionnaire assesses activation, health, training, and flexibility states on a 6-point Likert scale, ranging from 5 (i.e., I totally agree) to 0 (i.e., I agree not at all).

Psychological states

Psychological states prior to climbing were evaluated using Krane's (1994) MRF (Mental Readiness Form) questionnaire. This questionnaire was used to assess the participants' levels of cognitive anxiety (1: calm; 11: worried), somatic anxiety (1: relaxed; 11: tense), and self-confidence (1: confident; 11: scared) before climbing each boulder.

Climbing movement repertoire

Considering the challenge of exploring the movement repertoire of climbers in situ and under "real-world" conditions, participants' repertoire of climbing movements was indirectly assessed by examining the number of climbing movements they were unable to solve, both physically and cognitively. Specifically, if participants were unable to physically solve a movement and describe a climbing solution after the climbing procedure, it indicates that they were unfamiliar with this particular movement and that it had not yet been stored in their movement repertoire (Medernach, Henz, & Memmert, 2024). That is, they were unaware of potential movements and climbing actions they could use to successfully complete this movement.

Therefore, after the climbing procedure of each boulder, participants were asked to describe a strategy for solving those movements that they were unable to complete during the climbing period. Any movement for which they were unable to identify a climbing solution was designated as a "non-stored" movement. A high number of non-stored movements thus indicates that participants were unable to mentally describe how to climb those movements that they failed to solve during climbing.

Two climbing experts with considerable climbing qualifications (European Qualifications Framework: level 5), extensive climbing experience (≥14 years), and elite skill levels (≥25 IRCRA points) were tasked with assessing the number of non-stored movements. Findings revealed high consistency between the independent ratings of the experts (B1: $\kappa = .942$, $p < .001$; B2: $\kappa = .965$, $p < .001$).

Strategic decision-making

Given the similar climbing expertise of both groups (IRCRA scores, years of climbing, competitive experience, technical skills, and grip strength), and based on recent research identifying the movement repertoire as a pivotal factor contributing to optimal strategic planning of Olympic boulders (Medernach, Henz, Memmert, & Sanchez, 2024), examining the participants' strategic decision-making further provides indirect insights into their climbing movement repertoire. Accordingly, the two climbing experts in situ assessed the participants' route previewing times, climbing solution accuracy, and strategic adjustments during climbing. The experts' independent ratings indicated high consistency for all variables ($\kappa \geq .973$, $p < .001$).

Specifically, route previewing times provide insight into the duration climbers spent visually processing the boulders before attempting to climb them. Route previewing times thus indicate how much time participants required to understand the climbing movements and develop their climbing solutions (Medernach, Sanchez, et al., 2024). Therefore, previewing times reflect the participants' cognitive-motor expertise by indicating how quickly they understood the movement demands of the boulders and how fast they made their decisions.

Similarly, the participants' cognitive-motor expertise is further evidenced by the accuracy of their climbing solutions (Medernach, Sanchez, et al., 2024). Climbing solution accuracy was assessed using the SFAC framework (Suitability, Feasibility, Acceptability, Competitive advantage), originally proposed by Johnson and Scholes (1993). Specifically, the two experts independently rated the climbing solutions used in each boulder as either "unsuitable" (1), "feasible" (2), or "advantageous" (3). A climbing solution was classified as "unsuitable" if the plan for coordinating hand and foot movements was inappropriate for successfully climbing the boulder, resulting in failed climbing attempts. A "feasible" climbing solution resulted in the completion of the boulder, although linking hand and foot movements was not fully adequate, leading to visibly uncontrolled or jerky movement execution. A climbing solution was considered "advantageous" if the plan for coordinating movements enabled participants to efficiently climb the boulder, without uncontrolled or jerky movements.

In addition, a strategic adjustment was retained each time participants halted climbing movement execution because they were unable to grasp a target hold, thus impeding them to complete a particular movement. A low number of adjustments indicates an accurate interpretation of the climbing movements during route previewing, minimizing the need for strategic adaptations during climbing (Medernach et al., 2021).

Climbing performance

The two experts used video recordings to assess the participants' climbing performances, which included boulder completion (top rates, representing the number of climbers who successfully completed the boulders), the number of climbing attempts, and the highest climbing hold reached during the best attempt. The experts' independent ratings revealed absolute consistency for all variables ($\kappa = 1.00$, $p < .001$). Consistent with IFSC rules, a boulder was considered successfully completed when participants reached the uppermost hold with both hands and in a controlled position. A climbing attempt was recorded each time participants left the ground from the designated starting holds with all four limbs at the bottom of the boulder.

Statistical analyses

Statistical analyses (group comparisons, correlations) were conducted using IBM SPSS Statistics 29. Data are presented as mean values (M), followed by the 25th, 50th, and 75th percentiles. An alpha level of $p < .05$ (2-tailed) was used to determine statistical significance. MANOVAs (multivariate analysis of variance) were used to calculate differences between the groups regarding personal characteristics (age, height, weight), climbing expertise (IRCRA scores, experience, competitive experience, technical skills, grip strength), physical states (activation, health, training, flexibility), psychological states (cognitive anxiety, somatic anxiety, self-confidence), decision-making (route preview times, climbing solution accuracy, strategic adjustments), and climbing performance (top rates, attempts, highest reached hold). A priori power analyses were performed using G*Power. A priori power analysis for the MANOVA indicated a total sample size of $n = 48$ participants, with an effect size of $f = 0.340$, a power of (1-β) of .8, and an α of .05. Similar effect sizes have been reported in recent research in Olympic bouldering with comparable data collection procedures (Medernach, Henz, Memmert, & Sanchez, 2024).

Separate repeated-measures MANOVAs were conducted to compare each study group across the two boulders (from B1 to B2). A priori power analysis for the repeated-measures MANOVA indicated a total sample size of $n = 24$, with an effect size of $f = 0.432$, a power of (1-β) of .8, and an α of .05.

Eta-square was indicated as effect size. Levene's test was conducted to verify the homogeneity of variance and the Welch-test was used when the homogeneity of variances was violated. The Kolmogorov-Smirnov test was used to assess the normality of the variables. Independent t-tests were calculated to determine between-group differences. The nonparametric Mann-Whitney U-test was used when the assumptions for t-tests were violated. Cohen's d was calculated and converted to r for indicating the effect sizes between the groups. The Pearson correlation coefficient (r) was calculated to determine a significant relation between two variables. A priori power analysis for correlations revealed a sample size of $n = 48$ participants, with a power of (1-β) of .8, an α of .05, and a r value of .39.

Results

IFSC condition effect (Hypothesis 1)

In the B1 boulder, the RS group demonstrated a lower number of non-stored climbing movements compared to the NR group (see

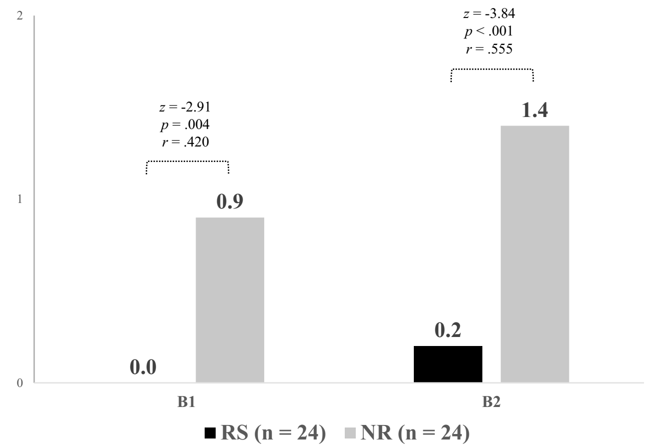

Figure 2. Number of non-Stored Climbing Movements in the B1 and B2 boulders for the Routesetter (RS) and Non-Routesetter (NR) group.

Table 2. Strategic decision-making and climbing performances of the Routesetter (RS) and Non-Routesetter (NR) groups in the B1 boulder (IFSC conditions).

Variable *(unit)*	RS (n = 24)	NR (n = 24)	*t/z*	*p*	*r*
Strategic decision-making					
Boulder previewing time (*seconds*)	32.1 (29.3/31.6/34.8)	47.4 (42.8/47.2/51.4)	$t = 10.08$	<.001	.824
Solution accuracy (*score*)	2.6 (2.0/3.0/3.0)	1.9 (1.0/2.0/3.0)	$z = -2.91$	.004	.420
Strategic adjustments (*number*)	0.6 (0.0/0.0/1.0)	2.2 (1.0/2.0/3.0)	$z = -4.36$	<.001	.629
Climbing performance					
Successful completion (*top rate*)	0.9 (1.0/1.0/1.0)	0.6 (0.0/1.0/1.0)	$z = -2.25$	.024	.325
Attempts at the boulder (*number*)	1.9 (1.0/2.0/2.8)	3.3 (2.0/3.0/4.8)	$z = -2.94$	.003	.425
Highest reached hold (*number*)	10.7 (11.0/11.0/11.0)	9.4 (7.0/11.0/11.0)	$z = -2.47$	.014	.356

Note. Results are presented as mean (*M*), followed by the 25th, 50th, and 75th percentiles in brackets, along with the *t*-test (*t*) or Mann-Whitney U-test (*z*) results, the *p*-values, and the effect sizes (*r*).

Figure 2), indirectly reflecting a superior climbing movement repertoire. In this context, results indicated a significant negative correlation between the number of non-stored movements and the routesetting expertise of the participants ($r = -.438$, $p = .002$). In addition, the MANOVA results revealed significant differences in strategic decision-making between the two groups, with Wilk's-Lambda $\Lambda = 0.250$, $F(3, 44) = 44.003$, $p < .001$, $\eta^2 = .750$. In particular, the RS group had shorter previewing times prior to attempting the B1 boulder, higher climbing solution accuracy scores, and fewer strategic adjustments while attempting the boulder (see Table 2). Furthermore, significant differences between the groups were also found in climbing performance, with Wilk's-Lambda $\Lambda = 0.758$, $F(3, 44) = 4.677$, $p = .006$, $\eta^2 = .242$. Specifically, the RS group was more successful in completing the B1 boulder, made fewer climbing attempts at the boulder, and reached higher climbing holds during their best attempts.

Time constraints effect (Hypothesis 2)

In the B2 boulder, the RS group demonstrated fewer non-stored climbing movements compared to the NR group (see Figure 2), further reflecting a superior climbing movement repertoire. Results indicated a significant negative correlation between the number of non-stored movements and the routesetting expertise of the participants ($r = -.569$, $p < .001$). Likewise, significant differences in strategic decision-making

Table 3. Strategic decision-making and climbing performances of the Routesetter (RS) and Non-Routesetter (NR) groups in the B2 boulder (time constraints conditions).

Variable *(unit)*	RS (n = 24)	NR (n = 24)	*t/z*	*p*	*r*
Strategic decision-making					
Boulder previewing time (*seconds*)	31.2 (29.2/31.4/33.5)	36.7 (34.7/37.4/39.3)	$t = 5.61$	<.001	.546
Solution accuracy (*score*)	2.3 (1.0/3.0/3.0)	1.4 (1.0/1.0/1.8)	$z = -3.22$	.001	.464
Strategic adjustments (*number*)	0.6 (0.0/1.0/1.0)	2.0 (1.0/2.0/3.0)	$z = -3.65$	<.001	.527
Climbing performance					
Successful completion (*top rate*)	0.7 (0.0/1.0/1.0)	0.3 (0.0/0.0/0.8)	$z = -3.14$	.002	.454
Attempts at the boulder (*number*)	1.7 (1.0/2.0/2.0)	2.3 (2.0/2.0/3.0)	$z = -3.09$	.002	.446
Highest reached hold (*number*)	10.4 (10.0/11.0/11.0)	7.7 (6.0/8.0/10.8)	$z = -3.73$	<.001	.539

Note. Results are presented as mean (*M*), followed by the 25th, 50th, and 75th percentiles in brackets, along with the *t*-test (*t*) or Mann-Whitney U-test (*z*) results, the *p*-values, and the effect sizes (*r*).

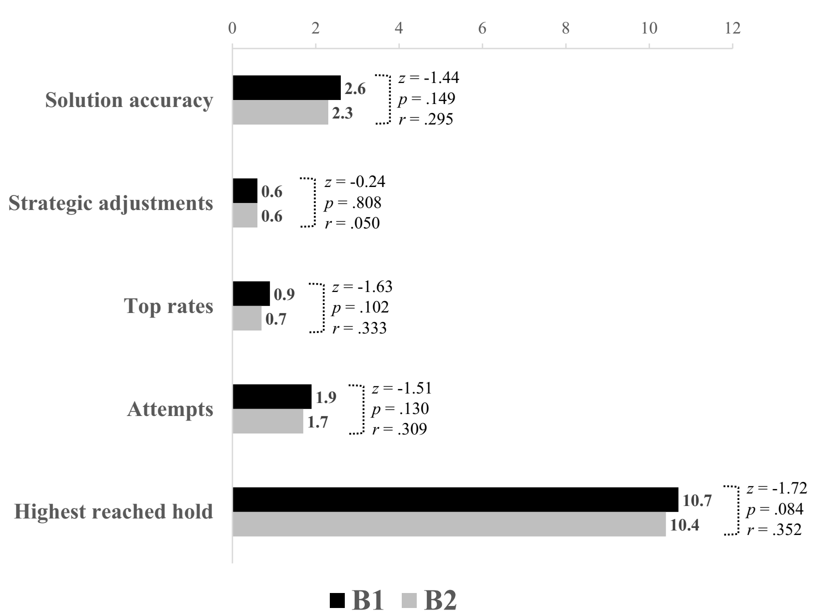

Figure 3. Climbing solution accuracy, strategic adjustments, and climbing performances of the routesetter group (RS) in the B1 and B2 boulders.

were observed between the two groups, with Wilk's-Lambda $\Lambda = 0.582$, $F(3, 44) = 29.353$, $p < .001$, $\eta^2 = .418$. Specifically, the RS group demonstrated shorter previewing times, superior climbing solution accuracy scores, and fewer strategic adjustments (see Table 3). Furthermore, significant differences between the groups were also found in climbing performance, with Wilk's-Lambda $\Lambda = 0.667$, $F(3, 44) = 10.523$, $p < .001$, $\eta^2 = .333$. In particular, the RS group was more successful in completing the B2 boulder, made fewer attempts, and reached higher holds during their best attempts.

In comparing the B1 (IFSC conditions) and B2 (time constraints conditions) boulders, the RS group demonstrated a similar number of non-stored climbing movements in both boulders (see Figure 2). Similarly, results indicated no significant differences in strategic decision-making for the RS group, with Wilk's-Lambda $\Lambda = 0.833$, $F(2, 22) = 2.202$, $p = .134$, $\eta^2 = .167$. Specifically, the RS group demonstrated comparable previewing times ($t = 1.21$ $p = .237$, $r = .123$), climbing solution accuracy scores, and strategic adjustments in both boulders (see Figure 3). Likewise, no significant differences in climbing performance were observed, with Wilk's-Lambda $\Lambda = 0.853$, $F(2, 22) = 1.892$, $p = .175$, $\eta^2 = .147$. In particular, the RS group demonstrated in both boulders similar top rates, number of attempts, and highest reached holds.

In contrast, the NR group demonstrated a higher number of non-stored climbing movements in the B2 boulder compared to the B1 boulder (see Figure 2). Similarly, results revealed significant differences in strategic decision-making, with Wilk's-Lambda $\Lambda = 0.190$, $F(2, 22) = 47.023$, $p < .001$, $\eta^2 = .810$. Specifically, the NR group had shorter previewing times in the B2 boulder (36.7 ± 4.1) than in the B1 boulder ($t = 10.09$, $p < .001$, $r = .718$). In addition, results revealed lower climbing solution accuracy scores in the B2 boulder, while no significant differences were observed in the strategic adjustments (see Figure 4). Likewise, results also indicated significant differences in climbing performance, with Wilk's-Lambda $\Lambda = 0.578$, $F(2, 22) = 8.028$, $p = .002$, $\eta^2 = .422$ (see Figure 4). In particular, the RS group demonstrated fewer top rates, a reduced number of attempts, and a lower highest reached climbing hold in the B2 boulder.

Discussion

The purpose of this study was to explore the role of the climbing movement repertoire as an underlying cognitive system in decision-making, climbing performance, and time constraint management in Olympic bouldering. To this end, elite climbers with professional routesetting expertise (RS) and similarly skilled and experienced climbers without any routesetting expertise (NR) were tasked with climbing two boulders under varying time constraints: four minutes for the first boulder (B1) and two minutes for the second boulder (B2). The results revealed that, in both boulders, the RS group demonstrated fewer non-stored climbing movements, enhanced strategic decision-making skills (shorter previewing times, more effective climbing solutions, fewer strategic adjustments), and superior climbing performances (higher top rates, fewer attempts, higher holds in best attempts). In addition, the RS group also demonstrated a smaller decline in non-stored climbing movements, strategic decision-making, and climbing performance when confronted with increased time constraints in the B2 boulder. Overall, the results of the present study highlight that elite climbers with routesetting expertise benefit from their extensive climbing movement repertoire, developed through long-term climbing expertise and additional routesetting practice, to make efficient strategic decisions, achieve optimal climbing performances, and effectively manage time constraints. The following sections critically discuss the results in the context of both hypotheses.

IFSC condition effect (Hypothesis 1)

In the B1 boulder under IFSC time conditions, the RS group demonstrated superior strategic decision-making skills

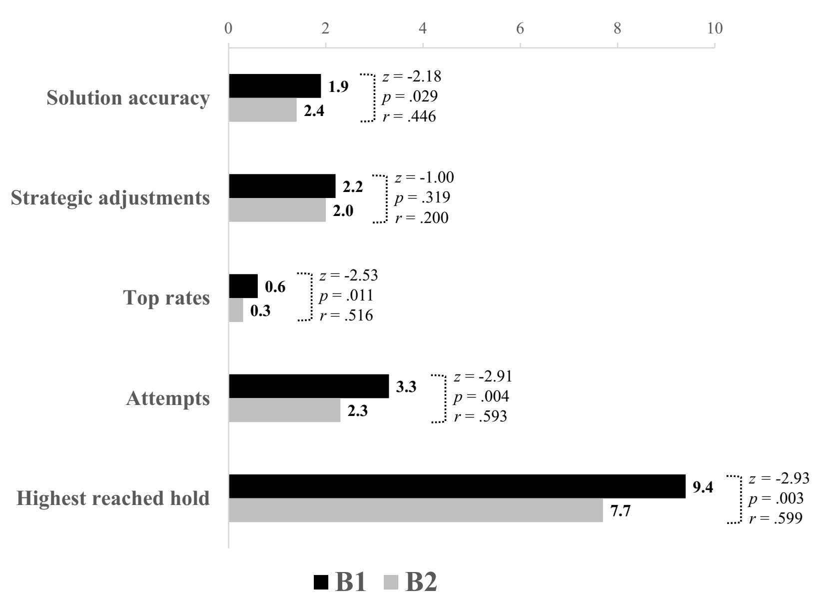

Figure 4. Climbing solution accuracy, strategic adjustments, and climbing performances of the Non-Routesetter group (NR) in the B1 and B2 boulders.

compared to the NR group, as evidenced by shorter route previewing times, more effective climbing solutions, and fewer strategic adjustments. Shorter previewing times indicate that participants in the RS group were faster in processing visual sensory input, anticipating the climbing movements, and developing potential climbing solutions (Medernach, Sanchez, et al., 2024). Despite these shorter previewing times, the RS group was more successful in developing effective climbing solutions and made fewer strategic adjustments, further indicating that climbers with routesetting expertise were better at interpreting and anticipating the climbing movements.

In the B1 boulder, the RS group also performed better compared to the NR group. These superior performances are unlikely to be attributed to personal characteristics (weight, height), climbing expertise (IRCRA scores, years of experience, technical skills, grip strength), physical states (i.e., the NR group reported even better training scores), or psychological factors (cognitive anxiety, somatic anxiety, self-confidence), given the non-significant differences between the two groups across the abovementioned variables. Instead, consistent with recent research on strategic planning in Olympic bouldering (e.g., Henz et al., 2025; Medernach, Sanchez, et al., 2024), superior climbing performances can largely be attributed to the enhanced strategic decision-making skills of the RS group.

Such better strategic decisions among the RS group merit further discussion. In fact, it is noteworthy that both groups comprised expert climbers, characterized by similar climbing skills and climbing backgrounds, with one exception, namely the routesetting expertise of the RS group. Clearly, this routesetting expertise appears to have provided climbers in the RS group a distinct advantage in their strategic decision-making and climbing performance. In this context, recent research has revealed that expert routesetters possess extensive abilities to mentally predict climbing movements and develop effective climbing strategies (Henz et al., 2024). Yet, this prompts the question of how routesetting expertise may have contributed to improved decision-making processes and superior climbing performance in the present study.

A key factor underlying these superior strategic decisions arises from the difference in the number of non-stored climbing movements between the two groups. This finding indicates that climbers lacking routesetting expertise were more likely to encounter difficulties in solving the climbing movements of the B1 boulder, both physically and cognitively. The fact that they were more often unable to identify a strategy to climbing the movements shows that they were unfamiliar with them, likely because they had not yet been stored in their repertoire. Therefore, better climbing performances, as a result of superior strategic decision-making, can be attributed, at least to a substantial extent, to a broader repertoire of climbing movements in the RS group, cultivated through their additional routesetting practice.

Indeed, professional routesetters, such as those in the present study, regularly engage in creating versatile and innovative climbing movements as part of their daily profession. Unlike climbers without such routesetting practice, they develop their movement repertoire not only through climbing, but also through the lens of routesetting, which further enhances their repertoire with innovative and creative movements. In this particular context, it is noteworthy that expert routesetters have recently reported that they are often not able to climb the boulders they create, particularly when setting for accomplished climbers (Henz et al., 2024). In other words, in their profession as routesetters, they do not necessarily rely on superior physical, technical, or motor skills, but rather benefit from perceptual and cognitive advantages.

Although further research is needed to gain deeper insights into the role of climbing movement repertoire, including a greater variety of climbing movements, the results of this study support Hypothesis 1 and suggest that climbers with routesetting expertise benefited from a broader climbing movement repertoire while attempting the B1 boulder. This enabled them, despite shorter previewing times, a more accurate processing of sensory input and a more effective anticipation of the climbing movements, leading to better strategic decision-making and superior climbing performances. Our findings align with recent research on strategic planning in Olympic bouldering (Medernach et al., 2025) and the movement repertoire paradigm (Medernach, Henz, & Memmert, 2024), which posits that numerous movement patterns stored in long-term memory help climbers to better decode incoming sensory information, identify climbing movement patterns, and anticipate climbing movements.

Time constraints effect (Hypothesis 2)

The findings from the present study suggest that such a broad repertoire of climbing movements also serves as an underlying cognitive system accounting for a better time constraint management. In fact, findings from the B2 boulder not only substantiate those observed in the B1 boulder—indicating fewer non-stored climbing movements, enhanced strategic decision-making, and superior climbing performances among the RS group—but also indicate that those climbers with routesetting expertise managed time constraints more effectively than those without such routesetting expertise.

To exemplify, while the RS group maintained consistent previewing times across both boulders, the NR group had shorter previewing times in the B2 boulder than in the B1 boulder. Clearly, these shorter previewing times in the NR group are associated with the reduced time available for processing the climbing movements and exploring potential climbing solutions. However, due to the increased time constraints in the B2 boulder, the NR group no longer had the time they actually would have needed to thoroughly process the climbing movements. In contrast, despite the increased time constraints, the available time was still sufficient for the RS group to effectively anticipate the climbing movements and develop their climbing solutions.

The need for more time to interpret the climbing movements among the NR group also explains why climbers without routesetting expertise showed a considerable decline in their strategic decision-making and climbing performances compared to the RS group when exposed to increased time constraints. In this context, the number of attempts made by both groups merits further consideration. In fact, more effective decision-making and fewer strategic adjustments account for the relatively low number of attempts made by the RS group, despite the increased time constraints in the B2 boulder. The NR group, however, made fewer attempts in the B2 boulder than in the B1 boulder. Similar to the previewing times, these findings indicate that climbers without routesetting expertise would have needed more attempts to explore the climbing movements. However, in the B2 boulder, increased time constraints limited the number of attempts they could make, further contributing to the decline in their climbing performance.

A key finding that also warrants further discussion emerges from the comparisons of non-stored climbing movements between the B1 and B2 boulders. Specifically, while the RS group maintained a similar number of non-stored climbing movements in both boulders, the NR group showed an increase in these non-stored movements in the B2 boulder, despite both boulders having a similar number of climbing movements, equal difficulty levels, and similar movement demands. While these findings provide further evidence that climbers with routesetting expertise were characterized by a more extensive repertoire of climbing movements, it remains to be discussed how increased time constraints contributed to more movements for which the NR group was unable to identify a climbing solution.

A possible explanation for this increase in non-stored movements among the NR group is that the reduced time for previewing and climbing resulted in higher demands on climbers' cognitive processing capabilities (Medernach et al., 2025). In fact, increased time constraints limit athletes' capacity for consciously processing visual sensory input, thereby imposing additional demands on their cognitive processing (Gröpel & Mesagno, 2019). In this context, research on decision-making in Olympic bouldering has revealed that increases in boulder complexity led to a decline in climbers' cognitive decision-making (Medernach et al., 2021). Therefore, consistent with Eysenck and Calvo's (1992) processing efficiency theory, the combination of increased time constraints and lower familiarity with the climbing movements in the NR group likely impaired their information processing capacity, contributing to cognitive bottlenecks. In contrast, a more extensive repertoire of climbing movements allowed climbers with routesetting expertise to be faster in processing sensory input and anticipating the climbing movements, thereby explaining their shorter previewing times and better strategic decision-making. This, in turn, is likely to have reduced the cognitive processing demands and led to a more effective management of time constraints.

Taken together, findings support our Hypothesis 2 and emphasize the role of climbing movement repertoire not only in decision-making and climbing performance, but also in effective time constraint management. A broad repertoire of climbing movement is essential for quickly processing sensory input and anticipating climbing movements by relying on cues from holds and comparing them with movement patterns stored in long-term memory. Without such a profound repertoire, climbers require more time to thoroughly process climbing movements and explore potential climbing solutions. This, in turn, can lead to insufficient time, negatively impacting their strategic decision-making and climbing performance.

The findings of this study are consistent with those of previous research across various sports, emphasizing that athletes rely on specific cues, contextual factors, and pattern recognition to quickly anticipate situations and make accurate decisions (e.g., Memmert. 2015, 2021; Williams & Jackson, 2019). Soccer players, for example, rely on postural cues from opponents, contextual information about player positions, and situational probability of actions to rapidly predict their opponents' forthcoming actions (e.g., Roca et al., 2013, 2021). Similarly, rugby players draw on their domain-specific motor repertoire to decode, predict, and counteract the actions of both teammates and opponents (e.g., Paolini et al., 2023). The findings from these studies, including the present one, emphasize that athletes' ability to quickly anticipate situations and make effective decisions is associated with superior visual and motor action representations (Makris & Urgesi, 2015). Therefore, domain-specific knowledge, such as a climber's movement repertoire, is essential for interpreting sensory input, decoding task-specific movement patterns, and quickly accessing retrieval structures in long-term memory (Cowan, 2008; Sala & Gobet, 2017). However, with regard to a critical view of experimental limitations, the present study may inspire further research on the movement repertoire paradigm, including female climbers, a greater variety of climbing movements, and a more direct assessment of climbers' movement repertoire.

Conclusion

The climbing movement repertoire constitutes a pivotal cognitive system underlying decision-making, climbing performance, and time constraint management in Olympic bouldering. An extensive repertoire of climbing movements enables climbers to rapidly anticipate climbing movements and identify effective climbing solutions by integrating sensory input with movement patterns stored in long-term memory. This enhances the speed of information processing and improves strategic decision-making, thereby helping climbers to more effectively manage time.

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Data transparency appendix

The Data that support the findings of this study are openly available: https://doi.org/10.7910/DVN/USAJIN

ORCID

Jerry Prosper Medernach http://orcid.org/0000-0003-1873-2704
Julian Henz http://orcid.org/0000-0001-7966-0092
Daniel Memmert http://orcid.org/0000-0002-3406-9175
Xavier Sanchez http://orcid.org/0000-0002-3498-0276

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