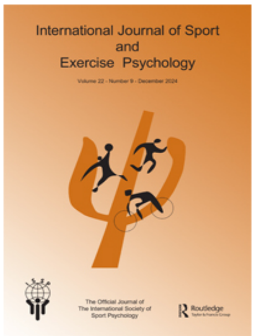

Routledge
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International Journal of Sport and Exercise Psychology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/rijs20

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To cite this article: Julian Henz, Xavier Sanchez, Daniel Memmert & Jerry Prosper Medernach (09 Jan 2025): Strategic decision-making in Olympic bouldering: the role of climbing movement repertoire examined, International Journal of Sport and Exercise Psychology, DOI: 10.1080/1612197X.2024.2449372

To link to this article: https://doi.org/10.1080/1612197X.2024.2449372

INTERNATIONAL JOURNAL OF SPORT AND EXERCISE PSYCHOLOGY
https://doi.org/10.1080/1612197X.2024.2449372

Strategic decision-making in Olympic bouldering: the role of climbing movement repertoire examined

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ABSTRACT

Bouldering is an Olympic climbing discipline performed on low-height climbing walls, referred to as boulders. Strategic decision-making is an essential, cognitive skill in Olympic bouldering, as climbers have limited time to solve a series of boulders. In developing strategic solutions, climbers draw upon their repertoire of climbing movements, which is conceptualised as high-level knowledge structures stored in long-term memory. Routesetters, those climbers who design and set boulders, possess an extensive movement repertoire, enabling them to create innovative boulders that challenge even highly skilled climbers. This study examined the movement repertoire paradigm as a cognitive system underlying strategic decision-making in Olympic bouldering. We conducted an in situ investigation under ecologically valid conditions by comparing the strategic decision-making skills and bouldering performances of elite climbers with extensive routesetting expertise (RS) to that of elite climbers without such expertise (NR) when tasked with solving an Olympic boulder. Data collection encompassed both strategic and performance-related parameters, including boulder previewing time, decision-making, strategic adjustments, and successful boulder completion. Findings revealed that RS demonstrated superior strategic decision-making, as evidenced by shorter previewing times, higher decision-making scores, fewer strategic adjustments, and were more successful at solving the boulder than NR. Findings provide evidence that routesetting expertise is beneficial for optimising strategic decision-making in Olympic bouldering. The diversity of movements routesetters encounter in their practice expands their movement repertoire. Such an extensive repertoire enables climbers to accurately decode movements and identify specific movement characteristics based on climbing hold configurations, thereby helping them to optimise their strategic decisions.

ARTICLE HISTORY
Received 6 June 2024
Accepted 23 December 2024

KEYWORDS
Cognition; matching theory; performance; routesetter; strategy

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Introduction

Bouldering, along with speed and lead climbing, is one of the three Olympic climbing disciplines. In Olympic bouldering, climbers are required to ascend a series of short climbing sequences on low-height artificial climbing walls known as boulders.

Each boulder typically includes a maximum of 12 climbing holds, with a designated starting position that requires climbers to be in a controlled position, placing both hands and feet on the marked starting holds. A boulder is considered successfully completed when climbers grasp the uppermost hold (referred to as the TOP) with both hands in a controlled position, or when they manage to stand on the top of the boulder (Hatch & Leonardon, 2023).

Among various factors that have been identified as critical for successful climbing performance, strategic decision-making is considered to be an essential, cognitive skill of climbers (see Sanchez et al., 2019; Medernach et al., 2024b). In Olympic bouldering, such strategic decision-making encompasses three key aspects: identifying effective climbing strategies before attempting boulders (Luis-del Campo et al., 2024; Medernach et al., 2024b), adapting strategies following unsuccessful climbing attempts (Künzell et al., 2021), and managing time efficiently during climbing (Mckellar et al., 2023; Medernach et al., 2016).

The initial, cognitive process of developing strategic solutions typically occurs during the previewing period of a boulder before climbing. During this planning phase, climbers seek to identify potential climbing strategies by visually processing climbing movements, gathering functional aspects from visual cues of holds, and mentally rehearsing climbing sequences (Morenas et al., 2021; Sanchez et al., 2012). Recent research has revealed that visual behaviour during pre-planning of boulders is influenced by climbers' sensorimotor expertise, resulting in experts climbing faster and spending less time fixating on holds they do not use during climbing (Luis-del Campo et al., 2024). Research has also shown that elite climbers are characterised by faster, more deliberate acquisition of perceptual cues, more efficient visual search strategies, and better identification of representative patterns during boulder previewing (Medernach et al., 2024c).

In examining climbers' strategic behaviour following unsuccessful attempts, Künzell and colleagues (2021) analysed a series of IFSC (International Federation of Sport Climbing) bouldering world cups. The authors observed that, after failed climbing attempts, developing new climbing strategies contributed more often to successful boulder completion than repeating the same strategy from previous attempts. Furthermore, in terms of time management, research has revealed that competitors typically make only three to five climbing attempts on each boulder, with each attempt averaging 20–40 s and rest times between attempts lasting about 30 s (Mckellar et al., 2023; Medernach et al., 2016; White & Olsen, 2010).

The critical role of strategic decision-making in Olympic bouldering is inherently related to the competition rules of the sport (see Hatch & Leonardon, 2023). In fact, bouldering competitions involve four to five distinct boulders that athletes must climb in a predefined order. Furthermore, competitors are given limited time to identify potential climbing strategies and subsequently climb these boulders. For example, in the qualifying and semi-final rounds of IFSC competitions, climbers have five minutes to successfully climb each boulder, followed by a five-minute rest period between two boulders. This accounts for the relatively low number of attempts they typically make (Augste et al., 2021) and requires climbers to quickly develop different climbing strategies for each boulder, which they are neither allowed to view nor to physically rehearse before the competition begins. In this context, it is relevant to mention that in Olympic bouldering, competitors are ranked according to the number of successfully climbed boulders and the number of attempts they needed to solve them. This further highlights the relevance of rapidly developing efficient problem-solving strategies in Olympic bouldering.

In addition to IFSC regulations, the critical role of strategic decision-making in Olympic bouldering is closely tied to the climbing movements involved in modern bouldering competitions (Neumann, 2019). In fact, over the past two decades, the design of boulders has evolved from mainly physically or technical demanding climbing sequences to an increasing focus on problem-solving skills that climbers need for achieving optimal performance. In response to the rising performance levels of competitors, routesetters have been compelled to consistently create innovative boulders that require original climbing solutions to ensure that only the best athletes make it to the top of the podium (Henz et al., 2024).

Routesetters are experienced climbers who are responsible for designing and setting the climbing movements that competitors encounter in Olympic bouldering (Augste et al., 2021; Tamerler, 2021). To design boulders with innovative and versatile movement sequences that challenge even highly skilled climbers, they require an extensive repertoire of climbing movements (Henz et al., 2024). According to the movement repertoire paradigm (Medernach et al., 2024a), such an extensive repertoire of climbing movements is essential for effectively interpreting and decoding climbing movements that climbers encounter in Olympic bouldering. The repertoire of climbing-specific movements can be conceptualised as high-level knowledge structures stored in long-term memory, enabling climbers to compare sensory input processed in short-term memory with movement patterns stored in long-term memory (Cowan, 2008; Sala & Gobet, 2017).

Thus far, research in the context of climbing has substantiated the importance of possessing an extensive repertoire of climbing movements for achieving optimal performance. For example, Ferrand et al. (2006) conducted interviews with elite climbers to gain insight into self-imposed handicaps in competitive climbing. Their findings revealed that climbers identified a lack of climbing route knowledge as a main factor impeding them to succeed in climbing competitions. Likewise, Sanchez and colleagues (2019) interviewed expert climbing coaches with the purpose of identifying factors that predict successful climbing performance. Among various performance determinants, the climbing movement repertoire was described as being of particular relevance for successfully planning climbing accents. Furthermore, Orth and colleagues (2018) observed that a pre-existing repertoire of behavioural capabilities influenced climbers' learning dynamics of body configuration patterns. Specifically, their finding suggest that learning processes depend upon the behavioural repertoire of climbers.

The movement repertoire paradigm in climbing builds upon the conceptual framework of the matching theory, which originates from Herrnstein's (1970) seminal research on behavioural responses to reinforcement. The pattern-matching theory posits that humans interpret sensory input by retrieving stored patterns from long-term memory when they need to choose from multiple potential responses (du Castel, 2015; Grossberg, 2005; Mace & Roberts, 1993). The ability to recognise relevant patterns is a fundamental, cognitive process for individuals when making decisions and anticipating future events (North et al., 2017). For example, tennis players rely on sport-specific knowledge structures to anticipate forthcoming actions and overcome time constraints (Williams & Ericsson, 2005). In the field of sports, experts' ability to quickly encode and retrieve meaningful patterns was initially explored in early research on cognitive processes that underlie expertise in chess. Specifically, de Groot (1956) and Chase and Simon (1973) proposed that chess grandmasters rely on meaningful patterns, such as familiar configurations of pieces or common opening moves, to memorise chess positions and develop effective strategies.

Since then, research on pattern recognition has been extended to various domains. For example, in-situ research on cognitive processes occurring during green reading revealed that professional golfers verbalised more statements related to planning and predicting performance outcomes than amateur golfers, who focused more on technical execution. That is, professional golfers demonstrated superior abilities in recognising relevant information, thereby enabling them to better plan and predict outcomes based on their expertise (Shaw et al., 2021). Furthermore, skilled soccer players were found to be faster and more accurate in recognising both familiar and unfamiliar soccer action sequences than their less-skilled counterparts (Williams et al., 2006). In addition, the visual behaviour patterns of expert sailors were found to differ from those of less experienced sailors during simulated navigation, including longer fixation recurrence times on irrelevant locations among experts (Manzanares et al., 2014). A further example arises from research on sight-reading in music, revealing that experts possess superior abilities to quickly identify clusters of notes (Sheridan et al., 2022).

To date, in situ research on climbers' movement repertoire under ecologically valid conditions is still sparse, and its role as an underlying, cognitive system for strategic decision-making remains largely unexplored. Yet, Olympic bouldering offers an interesting opportunity to examining the impact of domain-specific knowledge on individual behaviour within the sporting context for two main reasons (see Medernach & Memmert, 2021): firstly, competitors are allowed multiple attempts on each boulder (unlike in lead climbing, where only one attempt is allowed), enabling them to adapt and optimise their strategies over successive attempts, rather than committing to a single attempt; and secondly, boulders are relatively short, with difficulty compressed into just a few movements, making each one highly important and requiring detailed planning and precise decision-making.

Given that Olympic bouldering provides a unique setting to investigate the role of climbers' movement repertoire, this study aimed to deepen understanding of the factors that enable climbers to make efficient and strategic decisions by exploring the movement repertoire paradigm as a cognitive system underlying strategic decision-making of expert climbers. Our experimental approach builds upon the expert-performance framework initially proposed by Ericsson and Smith (1991) and involves comparing the strategic decision-making and bouldering performances of elite climbers with extensive routesetting expertise (RS) to that of elite climbers without such expertise (NR) when tasked with solving an Olympic boulder. The rationale for this study design is threefold: firstly, expert routesetters are considered to possess an extensive repertoire of climbing movements (Henz et al., 2024); secondly, it allows for a comparison of experts with similar, sport-specific backgrounds (see Williams & Ericsson, 2005), differing only in one aspect, namely their routesetting expertise; and lastly, including routesetters provides an original approach that offers valuable insights into those climbers who design movements of boulders, as they play a critical role in the current and future development of Olympic bouldering.

Drawing upon Herrnstein's (1970) pattern-matching theory and the related climbing movement repertoire paradigm (Medernach et al., 2024a), we hypothesised that climbers with routesetting expertise would demonstrate superior strategic decision-making abilities, compared to equal skilled climbers without such routesetting experience (Hypothesis 1: effect on decision-making). This is due to their superior climbing movement repertoire, developed through their routesetting expertise, which enables them to more effectively interpret and decode climbing movements by comparing perceived visual input with movement patterns retrieved from long-term memory. Furthermore, extending recent research revealing that success in Olympic bouldering is associated with climbers' ability to develop efficient climbing strategies (Medernach et al., 2024b), we hypothesised that better strategic decision-making would also contribute to superior bouldering performance among climbers with routesetting expertise (Hypothesis 2: effect on performance), despite both study groups having similar personal characteristics, sport-related backgrounds, and pre-performance physical and psychological states.

Materials and methods

Participants

The study required participants to meet the following criteria: climbers had to be at least 18 years old, to be in good health with no recent injuries that could have impacted their bouldering performances during data collection, and to have a bouldering ability level of at least 21 points on the IRCRA (International Rock Climbing Research Association) scale, thereby ensuring at least an advanced skill level (see Draper et al., 2016). Furthermore, climbers with routesetting expertise were required to have at least five years of experience in the field and to regularly engage in routesetting (i.e., at least once per week).

A total of 48 male climbers fulfilled these criteria and voluntarily participated in the study. Among them, 24 climbers had routesetting experience (RS group), while the remaining 24 climbers did not have such routesetting experience (NR group). The study did not include female climbers because only two potential participants with routesetting expertise met the required criteria. However, including them would have led to unbalanced group sizes and increased variability in physical and morphological characteristics. A priori power analysis with a power (1-β) of .80, an effect size $f^2(V) = .28$, and an α of .05 indicated a sample size of 48 participants for the MANOVA. The effect size in the power analysis was an estimate, as no similar studies are yet available, and was based on the findings of Henz et al. (2024). Participants from both study groups provided written informed consent and were given both verbal and written explanations regarding the purpose, content, and procedures of the study. The study was conducted in accordance with the ethical standards of the World Medical Association and received ethical approval from the University Ethics Committee (ID 229/2023).

As indicated in Table 1, both study groups had on average elite bouldering skills and over 10 years of bouldering experience, thereby confirming the extensive, domain-specific expertise of the participants (Ericsson, 2006). In this context, the RS group had

Table 1. Personal Characteristics and Bouldering Backgrounds of the two Study Groups.

Item (*unit*)	RS ($n = 24$)	NR ($n = 24$)	*t*	*p*	*r*
Age (*years*)	29.4 ± 5.5	27.6 ± 7.3	−0.94	.353	.137
Body weight (*kg*)	70.8 ± 7.3	72.2 ± 9.9	0.57	.574	.084
Height (*cm*)	177.2 ± 6.8	179.8 ± 6.3	1.39	.172	.200
IRCRA level at data collection (*score*)[1]	23.7 ± 1.8	23.7 ± 1.7	.083	.934	.011
All time highest IRCRA level (*score*)[1]	24.9 ± 1.9	24.7 ± 1.6	−0.42	.680	.063
Bouldering experience (*years*)	12.8 ± 4.8	11.8 ± 4.1	−0.75	.459	.110
Competitive bouldering experience (*years*)	5.4 ± 2.2	4.8 ± 2.6	−0.84	.408	.122
Technical climbing skills (*score*)[2]	3.5 ± 0.5	3.5 ± 0.6	−0.26	.794	.032
Grip strength (*kg*)[3]	60.4 ± 7.5	62.9 ± 9.1	1.21	.233	.176
Routesetting experience (*years*)	10.0 ± 4.1	none			

Note: Results are presented as *M* ± *SD*, followed by the reports from the t-tests and the effect size *r* for both study groups, climbers with routesetting expertise (RS) and without any routesetting expertise (NR).
[1]International Rock-Climbing Research Association's numerical scale for classifying climbing skill.
[2]Self-assessment using a 5-point Likert scale (1: poor; 2: fair; 3: good; 4: very good; 5: excellent).
[3]Assed prior to actual climbing testing using a calibrated Smedley Spring dynamometer.

an average of 10 years of professional routesetting expertise, whereas NR group had no such expertise. Furthermore, participants from the two study groups had similar personal characteristics and climbing backgrounds, with Wilks-Lambda $\Lambda = 0.839$, $F(9, 38) = 0.810$, $p = .610$, $\eta^2 = .161$. Specifically, pairwise comparisons revealed no significant differences between RS and NR in terms of age, weight, height, IRCRA levels, bouldering experience, technical climbing skills, and grip strength (see Table 1).

Since both physical (Saw et al., 2016) and psychological states (Sanchez et al., 2010) can potentially impact performance, we examined the physical and psychological states of the participants before the beginning of the experiment to identify factors that could influence their bouldering performance (see Data Collection section). While RS and NR were characterised by similar activation (3.9 ± 0.3, 4.1 ± 0.4, $t = 1.49$, $p = .144$, $r = .214$) and flexibility scores (4.0 ± 0.6, 3.9 ± 0.3, $t = -0.48$, $p = .632$, $r = .071$), NR had higher health scores (4.0 ± 0.3, $t = 2.37$, $p = .022$, $r = .330$) and training scores (4.0 ± 0.3, $t = 2.25$, $p = .029$, $r = .315$) than RS (health: 3.8 ± 0.3; training: 3.8 ± 0.3). Furthermore, between-group comparisons regarding the mental states of the participants before the beginning of the climbing procedure revealed no differences between RS and NR for cognitive anxiety (4.4 ± 2.2, 5.0 ± 2.3, $t = 0.91$, $p = .367$, $r = .134$), somatic anxiety (4.7 ± 2.0, 5.3 ± 2.3, $t = 1.02$, $p = .314$, $r = .148$), and self-confidence (3.6 ± 2.2, 4.4 ± 1.3, $t = 1.52$, $p = .136$, $r = .219$).

Experimental approach

Upon arrival at the climbing centre, participants read and signed the consent form, then completed a questionnaire to assess information about their personal characteristics and sport-related background. In line with IFSC rules for bouldering world cups, they had to remain within a designated isolation zone to prevent them from seeing the boulder before the start of the climbing procedure. In the isolation zone, they completed their routine warm-ups to optimally prepare themselves both physiologically and psychologically. Once climbers confirmed they were sufficiently warmed up and mentally prepared for climbing the boulder, their body weight, height, grip strength, physical states, and mental states were assessed (see Data Collection section).

After having completed these initial assessments and a standardised five-minute resting period, climbers were exposed to the boulder they had to solve during the climbing procedure. In accordance with IFSC rules for qualifying and semi-final rounds, they were given a five-minute time limit to preview and climb the boulder. Participants were tested individually, ensuring they could not observe other climbers during their attempts. Video recordings were made for the purpose of evaluating their bouldering performances. The climbing procedure was concluded under one of three conditions: when climbers successfully completed the boulder, when the five-minute time limit elapsed, or when climbers chose not to make any further attempts. Following the climbing procedure, a post-bouldering interview was conducted to gain additional insight into the participants' strategic decision-making.

Data collection

Personal characteristics and sport-related backgrounds

Body weight was measured in shorts and t-shirts to the nearest 0.1 kg using a Beurer scale. Body height was determined without shoes to the nearest 0.5 cm using a Seca 213 stadiometer. The bouldering ability levels of the participants were assessed using the IRCRA scale (see Draper et al., 2016), including both their highest bouldering grade they climbed at the time of data collection and their all-time best bouldering grade. Furthermore, their overall technical climbing skills were assessed using a 5-point Likert scale (i.e., 1: poor; 2: fair; 3: good; 4: very good; 5: excellent). Grip strength was measured using a calibrated Smedley Spring dynamometer, following a sport-specific test protocol. Specifically, participants were instructed to perform three repetitions with their dominant hand and by gradually applying maximum pressure for two seconds (see Medernach et al., 2015). The highest score obtained was recorded, with a standardised one-minute rest period between consecutive trials.

Physical and psychological states

Participants' physical states before the climbing procedure were assessed using Kleinert's (2006) PEPS (Perceived Physical State) questionnaire. This reliable and valid 20-item questionnaire evaluates the self-perceived states of activation, health, training, and flexibility 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 before the climbing procedure were assessed using Krane's (1994) MRF (Mental Readiness Form), which evaluated participants' levels of cognitive anxiety (1: calm; 11: worried), somatic anxiety (1: relaxed; 11: tense), and self-confidence (1: confident; 11: scared).

Strategic decision-making (hypothesis 1: effect on decision-making)

Climbers' strategic decision-making abilities were assessed in-situ by two bouldering experts (i.e., distinct from the routesetters who set the boulder for the study), with extensive bouldering qualifications (European Qualifications Framework: level 5), over 14 years of bouldering experience, and elite bouldering levels ($\geq$ 25 IRCRA points). Specifically, the two experts evaluated (a) climbers' boulder previewing times before climbing, (b) their strategic decision-making, and (c) strategic adjustments they made during actual climbing. Experts' independent ratings revealed high consistency for previewing times ($\kappa = .936$, $p < .001$), strategic decision-making ($\kappa = .935$, $p < .001$), and climbing strategy adjustments ($\kappa = .918$, $p < .001$). In addition, following the climbing procedure, a post-bouldering interview was conducted, including a semi-structured interview to gain further insights into climbers' strategic decision-making.

Previewing Times. Previewing times refer to the duration climbers spent visually processing climbing movements before physically attempting them. That is, short previewing times indicate of how quickly climbers were able to decode the climbing movements and develop their problem-solving strategies (Medernach & Memmert, 2021).

Strategic Decision-Making. Climbers' strategic decision-making was assessed by the two experts using the SFAC (i.e., suitability, feasibility, acceptability, competitive advantage) framework, originally proposed by Johnson and Scholes (1993). Specifically, in each attempt, climbers' strategic decision-making was rated as either unsuitable (1), feasible (2), or advantageous (3). Given that all climbers had elite bouldering ability levels and similar overall technical skill levels, this classification offered valuable insights into whether and how quickly participants were able to develop an appropriate problem-solving strategy. A strategic decision-making was considered to be "unsuitable" if the action plan for coordinating hand and foot movements was inappropriate for successfully climbing the boulder, resulting in a failed climbing attempt. "Feasible" strategic decision-making led to the completion of the boulder, although the coordination of hand and foot movements was not fully adequate, leading to visibly uncontrolled or jerky movement execution. Lastly, strategic decision-making was considered "advantageous" if the action plan for coordinating movements enabled climbers to execute climbing movements efficiently, without any uncontrolled or jerky motions, consequently minimising unnecessary movements and non-movement times.

Strategic Adjustments. While attempting the boulder, a climbing strategy adjustment was retained each time participants interrupted climbing movement execution because they were unable to grasp a target hold, thereby impeding them to complete a particular movement. A low number of strategic adjustments indicates a more accurate interpretation of the climbing movements during boulder previewing, requiring fewer ad hoc adaptations of the initial climbing strategy while attempting the boulder (Medernach & Memmert, 2021).

Post-Bouldering Interviews. In the initial question, participants were required to rate the difficulty of developing a climbing strategy to climb the boulder on a 6-point Likert scale (form 1: "hard" to 6: "easy"). In a second question, they were asked to rate their ability to develop a suitable climbing strategy (form 1: "not at all" to 6: "fully") and to evaluate the overall appropriateness of their strategic decision-making (form 1: "not accurate at all" to 6: "fully accurate"). In the final question, they were asked to specify, if applicable, whether an inappropriate strategic decision-making was the underlying cause of their inability to successfully climb the boulder (0: no; 1: yes).

Bouldering performance (hypothesis 2: effect on performance)

Similar to the assessment of strategic decision-making, the two experts also evaluated participants' bouldering performance using the video recordings. Climbing performance variables included (a) the number of participants who successfully completed the boulder (TOP rate), (b) the number of climbing attempts made on the boulder, (c) the highest reached climbing, and (d) the strategy-performance factor. The two experts' independent ratings revealed high consistency for the top rates ($\kappa = 1.000$, $p < .001$), the number of attempts ($\kappa = 1.000$, $p < .001$), and the highest reached climbing hold ($\kappa = 1.000$, $p < .001$).

Top Rate. In accordance with IFSC rules, a boulder was considered successfully completed when participants reached the designated finishing hold with both hands and in a controlled position.

Climbing Attempts. A climbing attempt was counted each time a participant began the boulder from the designated starting holds.

The Highest Reached Climbing Hold. This consisted of the highest climbing hold that participants were able to grasp in accordance with IFSC regulations during their best attempt.

Performance-Strategy Factor. In regard to Hypothesis 2, in which we hypothesised that better strategic decision-making would also contribute to superior bouldering performance, a performance-strategy factor was calculated by integrating climbing performance with strategic decision-making through the following equation: $\left(\frac{1+\sum_{i=1}^{n} \textit{strategy adjustments}}{\sum_{i=1}^{n} \textit{highest reached hold number}}\right) x \textit{ number of attempts}$. Specifically, the equation reflects strategic decision-making relative to the highest reached climbing hold and the number of attempts made by participants.

Design of the boulder

Two professional routesetters, each with a routesetting qualification (European Qualifications Framework: ≥ level 3), over 20 years of climbing experience, and elite bouldering skills (≥ 25 IRCRA points), were tasked with setting the novel boulder of the study. Given the relatively small community of expert routesetters, both routesetters were asked to keep their involvement confidential until data collection was completed. This was intended to prevent climbers with routesetting expertise from identifying who had set the boulder, thereby avoiding any potential advantage from familiarity with the setting style.

In accordance with IFSC rules, the boulder featured two starting holds, referred to as hold number one, and seven additional holds, with hold number eight designated as the TOP hold (see Figure 1). The boulder was intentionally designed to challenge participants' strategic problem-solving skills by including *capped* holds (i.e., holds covered by other holds to increase difficulty) and optional holds that were not essential for completing the boulder. The two routesetters assigned the boulder 20 points on the IRCRA scale, indicating that it matched the participants' ability levels and that it was theoretically climbable for them.

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. To test the hypotheses and minimise the impact of multiple testing, MANOVAs (multivariate analysis of variance) were conducted, assessing whether linear combinations of the dependent variables showed significant differences. Eta-square was used as the measure of effect size. Moreover, *T*-tests were calculated to determine between-group differences for the single

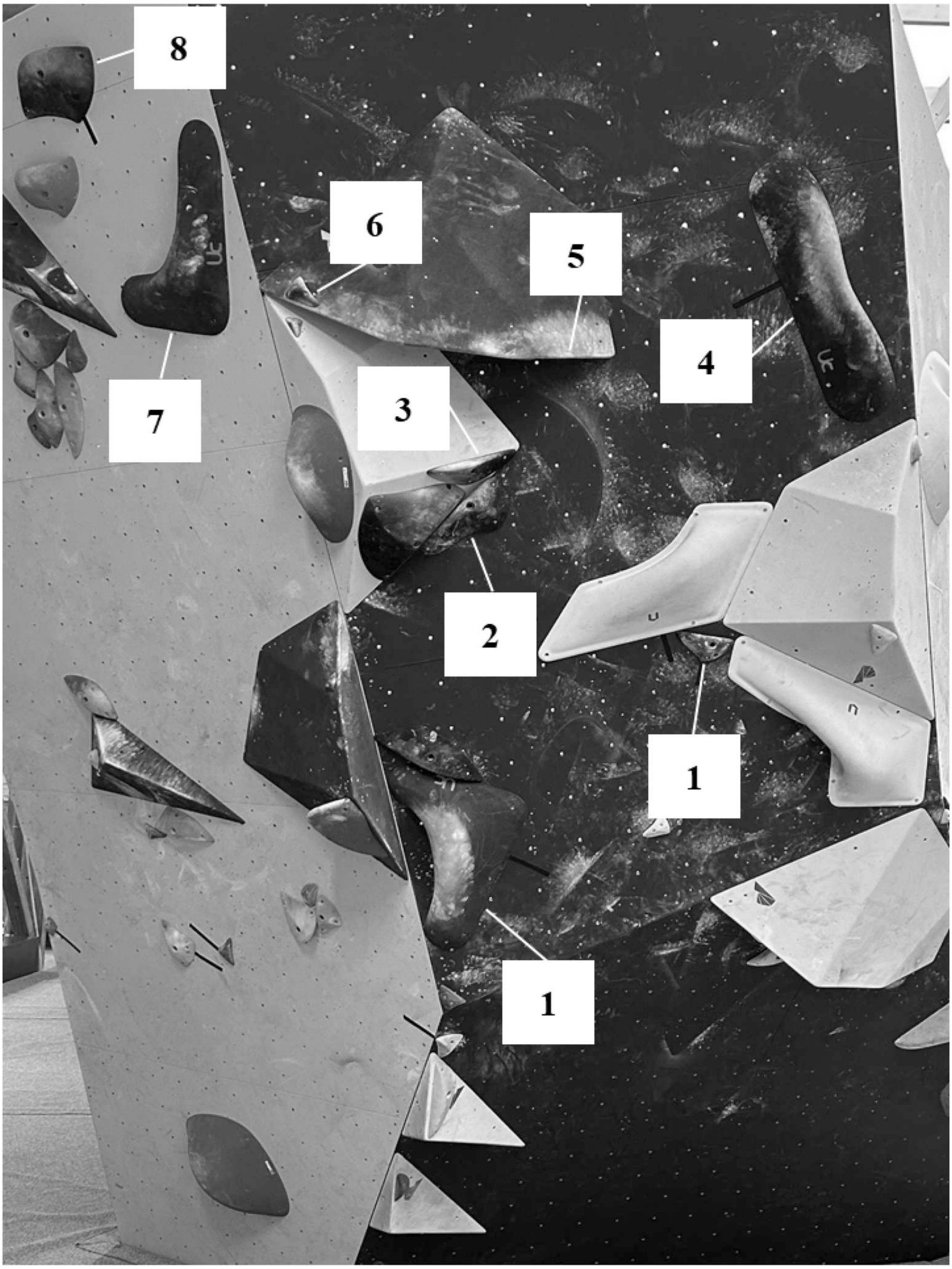

Figure 1. The Boulder of the Study.

Note: The boulder included two starting holds, marked as hold number one, along with seven additional holds, with hold number eight designated as the TOP hold.

variables. Levene's test was conducted to verify the homogeneity of variance, and the Welch-test was used when the homogeneity of variances was violated. Cohen's *d* was calculated and converted to *r* for indicating the effect sizes between the groups.

Transparency and openness

To adhere to the Transparency and Openness Promotion (TOP) guidelines, the manuscript includes appropriate citation for all data and materials used consistent with the journal's author guidelines. Methods employed in the analysis and materials used for conducting the research are clearly and precisely documented. Data is accessible (https://doi.org/10.7910/DVN/UTLZOA) for purposes of reproducing the results or replicating the procedure. Inclusion and exclusion criteria are outlined, and all measures are meticulously described.

Results

Strategic decision-making (Hypothesis 1: effect on decision-making)

Findings revealed significant differences in strategic decision-making between the two study groups for strategic decision-making, with Wilks-Lambda $\Lambda = 0.381$, $F(6, 41) = 11.104$, $p < .001$, $\eta^2 = .619$. Specifically, before attempting the boulder, RS (34.7 ± 5.7 s) had shorter previewing times compared to NR (46.8 ± 4.9 s, $t = 7.92$, $p < .001$, $r = .760$). RS demonstrated better strategic decision-making and made fewer strategic adjustments than NR (see Figure 2). In the post-bouldering interviews, NR (3.0 ± 1.3) reported finding it more challenging to develop a climbing strategy compared to RS (4.8 ± 0.8, $t = -5.49$, $p <$

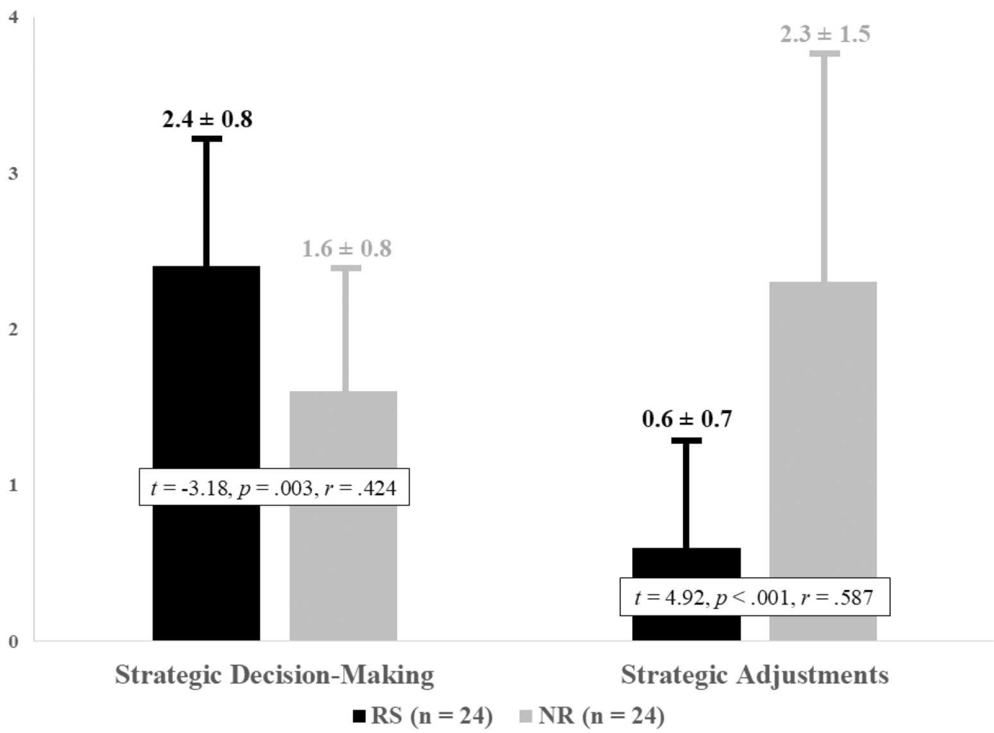

Figure 2. Strategic Decision-Making and Strategic Adjustments of the RS and NR group.

Note: The figure illustrates the mean ratings by the two climbing experts on strategic decision-making (1: unsuitable, 2: feasible, 3: advantageous) and the number of strategic adjustments for the climbers with (RS) and without routesetting expertise (NR).

.001, $r = .629$). Similarly, RS reported higher self-ratings regarding their ability to develop a climbing strategy (4.6 ± 0.9) and the appropriateness of their climbing strategy (4.9 ± 1.1) compared to NS (ability: 3.6 ± 1.1, $t = -3.48$, $p = .001$, $r = .456$; appropriateness: 3.7 ± 1.1, $t = -3.95$, $p < .001$, $r = .504$). Moreover, 93% ($n = 13$) of NR, in comparison to 20% ($n = 1$) of RS ($t = 4.39$, $p < .001$, $r = .753$), attributed their failure to successfully climb the boulder to inappropriate climbing strategies.

Bouldering performance (Hypothesis 2: effect on performance)

RS and NR differed significantly in terms of their bouldering performance, with Wilks-Lambda $\Lambda = 0.706$, $F(4, 43) = 4.478$, $p = .004$, $\eta^2 = .294$. Specifically, RS were more successful in completing the boulder (0.79 ± 0.4) and required fewer attempts for completion (2.2 ± 1.2) than NR (top rate: 0.41 ± 0.5, $t = -2.82$, $p = .007$, $r = .383$; attempts: 3.8 ± 1.8, $t = 3.45$, $p = .001$, $r = .453$). Similarly, RS reached higher climbing holds during their best attempts (7.6 ± 0.9) compared to NR (5.9 ± 2.0, $t = -3.71$, $p < .001$, $r = .480$). Furthermore, RS demonstrated superior performance-strategy factors than NR (see Figure 3).

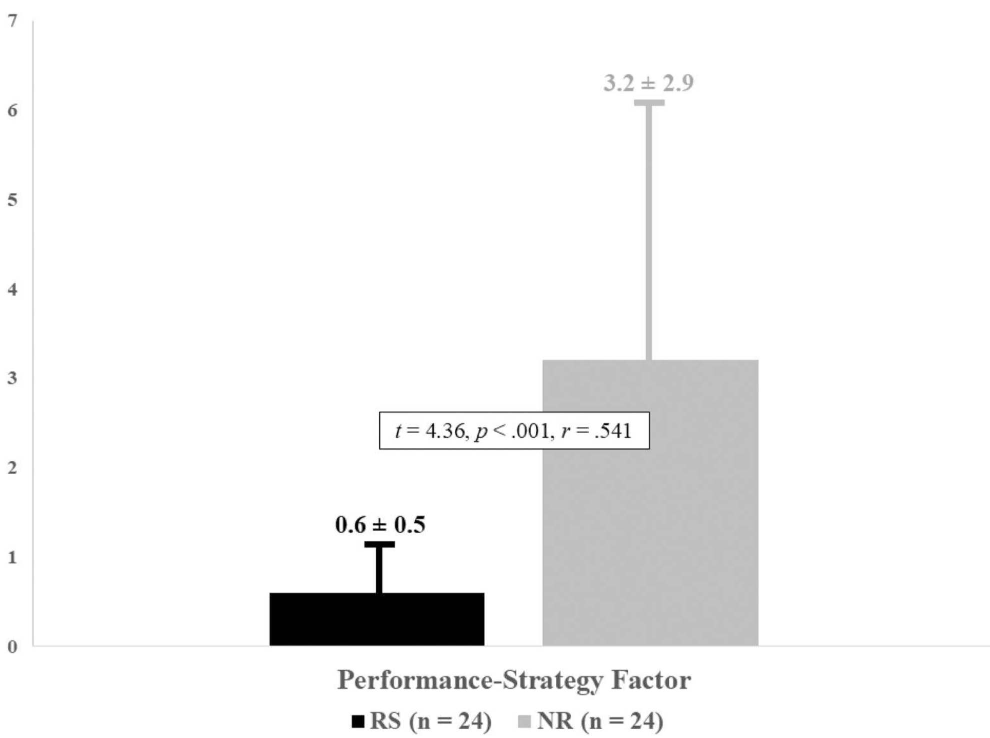

Figure 3. The Performance-Strategy Factors of the RS and NR group.

Note: The figure displays the performance-strategy factors of the climbers with (RS) and without routesetting expertise (NR), including their strategic decision-making relative to the highest hold reached during their best attempt and the number of attempts they made. Lower scores indicate superior bouldering performance relative to strategic decision-making.

Discussion

The aim of this study was to expand existing knowledge on factors that enable climbers to make efficient strategic decisions by exploring the movement repertoire paradigm as a cognitive system underlying strategic decision-making in Olympic bouldering. Building upon the expert performance framework by Ericsson and Smith (1991), we conducted an in situ, ecologically valid investigation to compare the strategic decision-making skills and bouldering performances of elite climbers with extensive routesetting expertise (RS) to that of elite climbers without such expertise (NR) when tasked with solving an Olympic boulder. Findings revealed superior strategic decision-making among RS, underpinned by shorter previewing times, better strategic decision-making scores, and fewer strategic adjustments. Furthermore, climbers with routesetting expertise were more successful at solving the boulder, with superior TOP rates, fewer attempts to complete the boulder, and higher reached climbing holds during their best attempts. In addition, RS also demonstrated superior performance-strategy factors than NR. Overall, findings indicate that RS demonstrated superior strategic decision-making and outperformed NR on the boulder, despite both groups having similar personal characteristics, sport-related backgrounds, and pre-performance physical and psychological states. In the following sections, we will discuss our findings in relation to both hypotheses.

Strategic decision-making (hypothesis 1: effect on decision-making)

Shorter previewing times observed in RS compared to NR indicate that climbers with routesetting expertise were faster in decoding the climbing movements and developing their problem-solving strategies compared to climbers without such routesetting expertise. Although self-reports should be interpreted with caution, findings from the post-bouldering interviews support this assumption, with RS indicating that they found it less challenging to develop a climbing strategy during boulder previewing than NR. Previous research on Olympic Bouldering has revealed that the ability to quickly decode climbing movements during boulder previewing is associated with climbers' skill level and their domain-specific expertise (Medernach & Memmert, 2021), with elite climbers requiring fewer scan paths and relying on more superficial previews compared to less-experienced climbers (Medernach et al., 2024b). Given that, in the present study, RS and NR had similar sport-related backgrounds, except for their routesetting expertise, it can be concluded that the faster decoding of climbing movements among RS is associated with the additional, domain-specific expertise that climbers with routesetting experience have, in contrast to those without such expertise.

Further findings from the present study corroborate the assumption that routesetting expertise is a beneficial skill for optimising strategic decision-making in Olympic bouldering. Specifically, in addition to shorter previewing times, RS also demonstrated better strategic decision-making and made fewer strategic adjustments while attempting the boulder. These findings suggest that RS more accurately interpreted the climbing movements during previewing and made better perceptual judgments of their climbing capabilities (Whitaker et al., 2019). The post-bouldering interviews substantiate superior strategic decision-making among RS, as climbers with routesetting expertise reported being better at developing a climbing strategy, rated their climbing strategies as more appropriate, and less often attributed failure to successfully climb the boulder to inappropriate climbing strategies compared to climbers without such routesetting expertise. Overall, these findings are consistent with recent research exploring the profile of expert routesetters in Olympic bouldering; among various skills required to set boulders, experts identified the ability to plan ahead of boulders and to develop effective climbing strategies as being of particular relevance (see Henz et al., 2024).

Making effective strategic decisions requires athletes to have a thorough understanding of the sport-specific context (Buekers et al., 2020). In other words, developing effective climbing strategies requires athletes to accurately interpret the movement demands of boulders, particularly when faced with challenging boulders that involve physically and technically demanding climbing movements (Medernach & Memmert, 2021). The conscious and deliberate decoding of climbing movements requires climbers to compare sensory input processed in short-term memory with movement patterns stored in long-term memory, allowing them to identify specific movement characteristics based on the arrangement of climbing holds (Medernach et al., 2024c). This ability to recognise meaningful climbing movement patterns depends on climbers' movement repertoire – the higher the number of movements stored, the more effectively climbers can identify movement patterns, anticipate climbing movements, and develop potential strategies for climbing boulders (Medernach et al., 2024a).

While experienced climbers with elite skill levels typically have such an extensive repertoire of climbing movements, expert routesetters additionally benefit from their large routesetting practice, in which they have explored and designed countless movement variations. This variety of climbing movements gained through routesetting also expands their movement repertoire, thereby enhancing their understanding of how to develop suitable climbing strategies and effectively execute climbing movements. Furthermore, their routesetting expertise likely affords them a different approach to processing climbing movements during boulder previewing. For example, expert routesetters know how to arrange climbing holds in a way that a climbing sequence requires a specific technique (e.g., cross movement). This knowledge may contribute to a more thoroughly scanning of boulders for specific cues that reveal the intentions of routesetters who designed them. In the context of the present study, for instance, climbers' routesetting expertise may have helped them to more quickly identify that the optional holds were not essential for completing the boulder but served as traps.

Taken together, findings from this study highlight the role of routesetting expertise and associated domain-specific high-level knowledge structures in the conscious and intentional development of effective strategic decisions in Olympic bouldering. The observed findings thus support our Hypothesis 1 and align with research from various sports domains, emphasising that experts benefit from superior perceptual-cognitive skills, particularly the ability to pick up relevant cues (Abernethy & Zawi, 2007) and to detect patterns (Williams et al., 2006), which help them to more effectively anticipate situations (Roca et al., 2018, 2021). These perceptual-cognitive skills emerge from prolonged, deliberate practice and can be attributed to the plasticity of underlying neuronal systems (Williams & Ericsson, 2005), resulting in enhanced encoding and retrieval processes in memory (Williams et al., 2011). In the context of Olympic bouldering, superior perceptual-cognitive skills account for the expertise-processing-paradigm, positing that experts are characterised by a faster and more conscious acquisition of perceptual cues, more efficient visual search strategies, and better identification of representative patterns among experts (Medernach et al., 2024c).

Bouldering performance (Hypothesis 2: effect on performance)

In the present study, elite climbers with routesetting expertise demonstrated better bouldering performances compared to similar skilled climbers without such routesetting expertise. While success in climbing is generally associated with multiple performance-determining factors (see Sanchez et al., 2019), the superior bouldering performances among RS are unlikely to be attributed to personal characteristics, technical abilities, or motor skills, given the similar findings across both study groups. Similarly, comparable PEPS and MRF scores observed in both groups make it less probable that physical and psychological states account for better bouldering performances observed among RS. In fact, NR had even higher health and training scores than RS, which would typically be expected to result in better performance. In contrast, superior strategic decision-making, fewer strategic adjustments, and stronger performance-strategy factors suggest that climbers with routesetting expertise demonstrated better bouldering performances due to their enhanced strategic decision-making, thereby supporting our Hypothesis 2.

Although further research is necessary to better understand the role of climbing movement repertoire – for instance by assessing eye tracking metrics during previewing of routesetters with varying skill levels, including female climbers, and examining the impact mental imagery vividness on strategic planning – findings align with recent research (see Medernach et al., 2024b); the importance of effectively decoding the movements of boulders and making appropriate strategic decisions to optimise performance in Olympic bouldering seems critical. This ability is closely linked to the movement repertoire of climbers, which enables them a more accurate and faster processing of visual sensory input by comparing the arrangement of climbing holds with movement patterns stored in long-term memory. Similar to expert musicians (Sheridan et al., 2022) or chess grandmasters (Connors et al., 2011), such domain-specific high-level knowledge structures are compelling to accurately process sensory input by relying on movement patterns stored in long-term memory. Therefore, climbers who possess such an extensive movement repertoire are more likely to make better decisions, which, in combination with proficient technical and motor skills, also contributes to superior bouldering performance. This is because domain-specific knowledge, such as climbers' 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, aligned with the debate on the Mozart effect (Schellenberg & Lima, 2024), these high-level knowledge structures risk being confined to the modality of Olympic bouldering. Therefore, further research on the movement repertoire paradigm across other climbing disciplines is necessary to gain a better understanding of its role in strategic decision-making and achieving successful climbing performance.

Conclusion

A key objective of the expert-performance framework is to understand how experts develop the skills that explain their superior performance (Williams & Ericsson, 2005).

The present study provides evidence that routesetting expertise is a key skill for optimising strategic decision-making in Olympic bouldering. Overall, our findings indicate that climbers with routesetting expertise outperformed those without such expertise in both bouldering performance and strategic decision-making; they had shorter previewing times, better decision-making scores, fewer difficulties in developing climbing strategies, and fewer strategic adjustments. Findings suggest that the climbing movement repertoire paradigm is the cognitive system underlying superior strategic planning among climbers with routesetting expertise. Indeed, routesetting provides climbers with a valuable opportunity to expand their movement repertoire by deliberately exploring countless movement variations and designing creative climbing sequences. Such an extensive repertoire of climbing movements allows climbers to accurately decode the movement demands of boulders by comparing perceived stimuli with movement patterns stored in long-term memory. This enables them to recognise familiar climbing movements based on the arrangement of the climbing holds. In other words, an extensive repertoire of climbing movements is essential for optimising strategic decision-making in Olympic bouldering.

Data availability statement

Supplemental data for this article can be accessed online at https://doi.org/10.1080/1612197X.2024.2449372.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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