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Cognitive-behavioural processes during route previewing in bouldering☆

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ABSTRACT

Introduction: In the Olympic climbing discipline of bouldering, climbers can preview boulders before actually climbing them. Whilst such pre-climbing route previewing is considered as central to subsequent climbing performance, research on cognitive-behavioural processes during the preparatory phase in the modality of bouldering is lacking. The present study aimed at extending existing findings on neural efficiency processes associated with advanced skill level during motor activity preparation by examining cognitive-behavioural processes during the previewing of boulders.
Methods: Intermediate ($n = 20$), advanced ($n = 20$), and elite ($n = 20$) climbers were asked to preview first, and then attempt two boulders of different difficulty levels (boulder 1: advanced difficulty; boulder 2: elite difficulty). During previewing, climbers' gaze behaviour was gathered using a portable eye-tracker.
Results: Linear regression revealed for both boulders a significant relation between participants' skill levels and both preview duration and number of scans during previewing. Elite climbers more commonly used a superficial scan path than advanced and intermediate climbers. In the more difficult boulder, both elite and advanced climbers showed longer preview durations, performed more scans, and applied less often a superficial scan path than in the easier boulder.
Conclusion: Findings revealed that cognitive-behavioural processes during route previewing are associated with climbing expertise and boulder difficulty. Superior domain-specific cognitive proficiency seems to account for the expertise-processing-paradigm in boulder previewing, contributing to faster and more conscious acquisition of perceptual cues, more efficient visual search strategies, and better identification of representative patterns among experts.

1. Introduction

Indoor Bouldering is an Olympic climbing discipline that requires athletes to complete short, physically and technically demanding climbing sequences on low-height artificial climbing walls (Hatch & Leonardon, 2023). Before attempting boulders, climbers typically apply a preview to process visual sensory input and perceive relevant information, such as the orientation and graspability of climbing holds (Morenas et al., 2021). During the so-called boulder previewing, climbers rely on their perceptual and cognitive skills to develop efficient climbing strategies coupled with appropriate motor actions (Medernach & Memmert, 2021; Whitaker et al., 2019). Although boulders are relatively short in length with typically less than 12 climbing holds (Hatch & Leonardon, 2023), versatile climbing movements put climbers at risk of misinterpreting movements and developing inappropriate climbing strategies that can rarely be adjusted once they have attempted the movements (Medernach & Memmert, 2021; Seifert et al., 2017) (see Fig. 1).

Marteniuk, 1976 originally described perceptual-cognitive expertise as the ability to identify and process environmental information, and to integrate sensory input with existing knowledge to plan and execute appropriate and goal-directed motor actions. In the ecological dynamics

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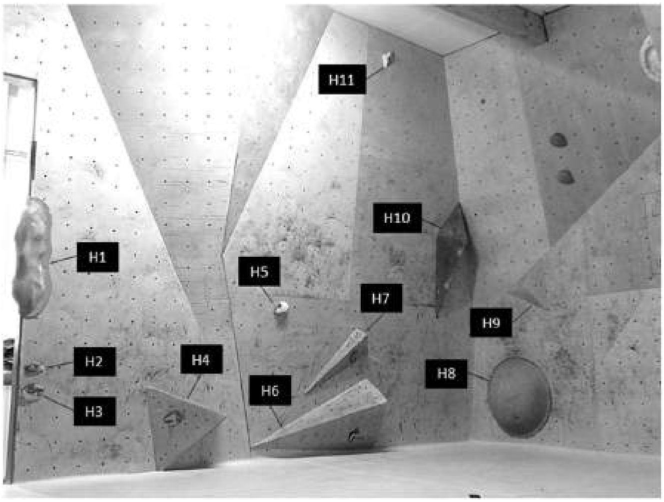

Figure 1. Boulder 1 of the study.

framework, athletes operate in a dynamic performer-environment reciprocity (Araújo et al., 2017); this implies that perception, cognition, and motor action are considered as highly coupled systems that intertwine in activity (Renshaw et al., 2019). Considering that motor actions typically require the integration of perceptual information processed in working memory with movement patterns stored in long-term memory (Cowell et al., 2019; Roca & Williams, 2016), 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).

In their seminal work on motor learning and skill acquisition, Fitts and Posner (1967) proposed a model with three successive phases involved in motor skill acquisition: (a) the initial cognitive stage, in which individuals concentrate on understanding tasks and selecting appropriate motor actions, requiring high cognitive effort and explicit knowledge; (b) the associative stage, in which practice contributes to movement proficiency, allowing individuals to increasingly focus on task-specific details; and (c) the final autonomous stage, in which movements are automatised and require minimal conscious effort. Fitts and Posner (1967) considered motor learning from an information-processing perspective, acknowledging high attentional demands and limitations of human processing capacity in learning new skills. Modern learning theories for a wide range of motor tasks draw on Fitts and Posner's model, as they typically exhibit initial learning phases of rapid performance increases, followed by gradual phases in which performance gains accrue much slower (Denison & Markula, 2023; Taylor & Ivry, 2012).

The neural efficiency hypothesis, originally proposed by Haier et al. (1988), posits that experts with superior perceptual and cognitive abilities exhibit more efficient patterns of neural activity when performing cognitive tasks. Accordingly, superior task-specific cognitive proficiency contributes to a more efficient recruitment and utilisation of cortical resources (Babiloni et al., 2010; Del Percio et al., 2009; Immink et al., 2020). Research using neuroimaging techniques, in particular functional magnetic resonance imaging (fMRI) or electroencephalography (EEG), has provided insights into the physiological mechanisms underlying the neural efficiency hypothesis by measuring cerebral cortical activity during motor preparation. Along with motor expertise, plastic changes occur in the neuronal structures involved in movement planning and execution control, in their information processing activity, and their connectivity (Lohse et al., 2014; Tremblay et al., 2021). Specifically, improvements in cognitive-motor processes contribute to the transfer of executive information from the associative/prefrontal to the sensorimotor network (Coynel et al., 2010), leading to a decrease in activity of cortical regions involved in motor learning, conscious control of motor processes, and integration of sensory stimuli (e.g., dorsolateral prefrontal cortex, anterior cingulate cortex) with increasing practice (Hatfield, 2018; Wu et al., 2015). Conversely, areas of the frontal cortex and the anterior parts of the caudate nucleus became more active again when individuals were asked to pay particular attention to the execution of already automated movements (Wu et al., 2014).

In terms of neuroplastic adaptations and the associated motor skill automaticity, research across various sport domains has resorted to the expert-novice paradigm to highlight that experts benefit from superior perceptual and cognitive skills, particularly in open and dynamic sports with highly time-constrained motor actions (Furley et al., 2013; Van Maarseveen et al., 2018), such as soccer (Roca et al., 2011; Ward & Williams, 2003), badminton (Hagemann et al., 2006), or martial arts (Müller & Abernethy, 2012). Findings from these studies have provided evidence that experts are more successful in predicting probable outcomes (e.g., Mann et al., 2007; Roca et al., 2011), to benefit from better anticipatory behaviour (e.g., Roca & Williams, 2016; Williams & Jackson, 2019), and to be more efficient in their decision-making (e.g., Roca & Williams, 2017). Experts' superior anticipation and problem-solving skills are assumed to be associated with a more conscious pickup of relevant environmental information (e.g., Ward & Williams, 2003; Williams et al., 2018) and perceptual cues (e.g., Roca & Williams, 2016; Williams & Jackson, 2019), more efficient visual search strategies (e.g., Ericsson, 2017; Mann et al., 2007), and a better identification of representative patterns (e.g., Roca & Williams, 2016; Smeeton et al., 2004).

In recent years, research on perceptual and cognitive skills has also expanded to less open sports with more stable environments (e.g., without direct opposition). Golf players, for instance, rely on their perceptual-cognitive skills to analyse slops, breaks, and green contours for identifying the optimal trajectory of the ball (Carey et al., 2017). Parkour practitioners use visual search skills to explore environmental features (Grosprêtre & Gabriel, 2020) and develop motor actions that enable efficient interaction with obstacles (Strafford et al., 2021). Similar to golf and parkour, Olympic bouldering involves relatively stable environments, yet climbing movement variability requires climbers to accurately process movement information (Pietsch & Jansen, 2018) and constantly adjust their climbing strategies (Medernach & Memmert, 2021). Visual processing of climbing tasks prior to climbing is considered critical for achieving optimal climbing performance (Sanchez et al., 2019); it allows climbers to interpret visual sensory input, identify efficient climbing strategies, and develop appropriate motor actions (Medernach & Memmert, 2021; Whitaker et al., 2019).

The emergence of climbing as a competitive sport – including the modality of bouldering – has also aroused research interest in route previewing in recent years. Route previewing has been found to positively affect climbing fluency (Seifert et al., 2017) and contribute to fewer and shorter non-movement times during climbing (Sanchez et al., 2012). In the modality of bouldering, Morenas et al. (2021) investigated the impact of different types of preview on climbing performance. Their findings revealed that real-mode previewing resulted in more successful boulder completions, whereas climbers showed more failed climbing attempts when no preview was performed. In this regard, previous research also assumes that previewing strategies depend on climbing difficulty and complexity (Button et al., 2016; Grushko & Leonov, 2014).

Despite increasing research on previewing in climbing, little is known about cognitive-behavioural processes during the preparatory phase in the modality of bouldering. Further research into perceptual mechanisms and cognitive-behavioural processes involved in boulder previewing is essential, particularly because bouldering involves distinctly shorter climbing sequences than sport climbing (Hatch & Leonardon, 2023); it remains to be tested to what extent previous findings from sport climbing may apply to the modality of bouldering. Therefore, the present study aimed at extending existing findings on neural efficiency processes associated with advanced skill level during motor activity preparation by examining cognitive-behavioural processes in climbers of different skill levels, including gaze behaviour and self-reported strategies during the previewing period of boulders of varying difficulty. This study seeks to provide complementary and compelling insights into essential perceptual and cognitive mechanisms underlying superior cognitive-motor performance in the increasingly popular Olympic discipline of bouldering. It was assumed that visual information processing during the preview would be associated with domain-specific expertise. Thus, extending Pezzulo et al. (2010) and Sanchez et al. (2019), we hypothesised that (hypothesis 1) elite climbers would produce shorter preview durations and fewer scans of the boulders than advanced and intermediate climbers, as their sport-specific movement knowledge contributes to a faster processing of climbing movements. Moreover, following Grushko and Leonov (2014), we hypothesised that (hypothesis 2) elite climbers would more often rely on superficial scanning to preview the boulders, as in-depth movement analysis is less compelling for them to perform successful motor actions. Lastly, drawing on Pezzulo et al. (2010), we hypothesised that (hypothesis 3) visual information processing during previewing would also be related to the difficulty of the boulder; preview duration and number of scans would increase, and the scan path would consist of a more in-depth movement analysis as the difficulty of the boulder increases.

2. Materials and methods

2.1. Participants

Sixty male climbers took part in the study (see Table 1 for details); all provided written informed consent and were informed verbally and in writing about the purpose, content, and procedures of the experiment. The study was conducted in conformity with the World Medical Association and received ethical approval from the University Ethics Committee (ID 057/2020). Participants were at least 18 years old, healthy, and had not suffered any recent injuries that could have affected their bouldering performance during the experiment. Considering that they had to climb the boulders, they were required to have at least three months of bouldering experience to ensure basic climbing skills. Female athletes were excluded to best limit factors inherent to morphology characteristics (e.g., reachability of climbing holds) influencing bouldering performance.

Table 1
Personal characteristics and sport-specific backgrounds of the study groups.

Variable (*unit*)	Intermediate (INT)	Advanced (ADV)	Elite (ELI)	Between Groups
Participants (*number*)	20	20	20	
Age (*years*)	27.4 ± 3 [26, 29]^{ADVb}	29.5 ± 8 [26, 33]^{ELIb}	25.6 ± 4 [24, 28]^{INTb}	$H(2) = 2.83^{b}$
Body weight (*kg*)	70.3 ± 5 [68, 73]^{ADVc}	67.2 ± 3 [66, 69]^{ELIb}	68.2 ± 5 [66, 71]^{INTb}	$F(2, 59) = 2.30^{b}$
Body height (*cm*)	180.3 ± 4 [178, 182]^{ADVb}	178.4 ± 4 [177, 180]^{ELIa}	178.8 ± 4 [177, 181]^{INTb}	$F(2, 59) = 1.24^{b}$
IRCRA (*score*)[1]	16.2 ± 1.0 [16, 17]^{ADVe†}	20.5 ± 0.9 [20, 21]^{ELIe†}	25.0 ± 0.9 [25, 26]^{INTe†}	$H(2) = 34.29^{e\dagger}$
Experience (*years*)	2.2 ± 1.0 [2, 3]^{ADVe†}	6.6 ± 2.5 [5, 8]^{ELId†}	10.0 ± 4.1 [8, 12]^{INTe†}	$H(2) = 26.92^{e\dagger}$
Preview skills (*score*)[2]	2.5 ± 1.0 [2.1, 2.9]^{ADVc†}	3.4 ± 0.8 [3.1, 3.6]^{ELId†}	4.3 ± 0.6 [4.0, 4.5]^{INTe†}	$H(2) = 15.35^{d\dagger}$

Note. Results are indicated as $M \pm SD$, followed by the 95% CI in square brackets. Comparisons between two groups are displayed as superscripts characters behind the square brackets, including the group being compared (^{INT}; ^{ADV}; ^{ELI}), the effect size r (^{a} $r < 0.1$; $^{b}.1 \leq r < 0.3$; $^{c}.3 \leq r < 0.5$; ^{d} $0.5 \leq r < 0.7$; ^{e} $r \geq 0.7$), and the symbol † if significant ($p < 0.05$). The last column shows for each item either the ANOVA (F) or the Kruskal-Wallis (H) results, followed by the effect size and the symbol † if significant ($p < 0.05$), indicated as superscripts.

[1] Assessed using the International Rock Climbing Research Association's numerical scale for classifying climbing skill.

[2] Self-assessment using a 5-point Likert scale (i.e., 1: poor; 2: fair; 3: good; 4: very good; 5: excellent).

To gain insight into the extent to which perceptual mechanisms and cognitive-behavioural processes during previewing are associated with skill level, participants were assigned according to their reported bouldering grades (i.e., hardest boulder they managed to climb at the time of the investigation) to the intermediate (INT, with $n = 20$), advanced (ADV, with $n = 20$), or elite (ELI, with $n = 20$) group. This resulted in a balanced distribution of climbers with similar skill levels within each study group. Bouldering grades were determined using the IRCRA scale (i.e., International Rock Climbing Research Association), a numerical scale that is considered reliable and valid for classifying climbing ability (Draper et al., 2016). Specifically, the IRCRA scale comprises five successive levels, with beginner (IRCRA score: ≤10), intermediate (IRCRA score: 11–17), advanced (IRCRA score: 18–23), elite (IRCRA score: 24–27), and world class level (IRCRA score: ≥28). Additionally, participants were asked to rate their boulder previewing skills using a 5-point Likert scale (i.e., 1: poor; 2: fair; 3: good; 4: very good; 5: excellent).

2.2. Overview of the study

Participants were exposed to two novel boulders varying in difficulty (see Design of the boulders section), which included climbing movements climbers commonly encounter in modern bouldering. Upon arrival at the test centre, participants had to fill out a consent form and were informed of their right to leave the experiment at any stage. To avoid pre-fatigue affecting their climbing performance, they were advised to a 48-h rest period prior testing, during which they should avoid any non-essential physical activity. Following IFSC (International Federation of Sport Climbing) climbing procedures, they were required to remain in an isolation zone (i.e., separate bouldering area) before the beginning of the experiment to avoid early exposure to the boulders.

In the isolation zone, participants completed an individual warm-up programme of a standardised 20-min duration, including familiarisation trials on boulders that were excluded from data collection. After completing the warm-up, they were given a standardised 5-min rest period during which the eye-tracker device was attached to their head. In line with Mitchell et al. (2020), a nine-point calibration procedure was conducted to ensure the accuracy of the eye-movement recorder. To this end, participants were asked to focus on nine visual dots spread across a bouldering wall, with the markers placed at the outermost areas of the visual field.

Once the calibration procedure was completed and participants felt confident to start the experiment, they began previewing boulder 1, during which gaze behaviour was assessed. In agreement with Mitchell et al. (2020), participants had to remain in a defined area 3 m away from the boulder. This allowed for realistic viewing conditions (Kredel et al., 2017; Roca et al., 2013) with an optimal viewing angle of all climbing holds (i.e., participants were allowed to move their head), and ensured that participants remained within the recordable visual field of the eye-tracker. Participants were not given any information about the difficulty nor about the climbing movements of the boulder. In line with IFSC rules, they were prohibited from rehearsing the boulder before or during the preview. As in international bouldering competitions, participants were given a 5-min time limit to preview and subsequently attempt the boulder (Hatch & Leonardon, 2023). The time limit was measured using a digital clock display visible to all participants.

After completing the preview (i.e., by verbally notifying to the examiner), time was halted, and participants were asked to fixate the starting hold of the boulder to verify any offset of the eyeglasses. The eye-tracker device was taken off and participants had to turn their back to the climbing wall to prevent a further inspection of the boulder, which could have affected their subsequent climbing performance. A post-preview interview, lasting approximately 30 s, was conducted to assess verbal reports.

Following the post-preview interview, participants attempted to climb boulder 1 within the remaining time of the 5 min they had left after the previewing procedure. The first part of the experiment ended upon three scenarios: when the participant achieved the top hold (i.e., successful completion), when the 5-min time limit was reached, or when the participant decided to not perform further attempts. After each attempt at the boulder (i.e., time was stopped for this purpose) and at the end of the experiment (post-bouldering interview), participants were asked to indicate whether failed movement attempts (i.e., unsuccessful attempt that resulted in falling off the wall) were associated with an inappropriate climbing strategy. As per IFSC regulations, participants were given in the next step a standardised 5-min rest before repeating the experimental procedure for boulder 2.

2.3. Data analysis

2.3.1. Eye-tracker metrics

Gaze behaviour was assessed using the portable, head mounted ASL Mobile Eye-XG eye-tracker (Applied Science Laboratories, Bedford, MA). The eye-tracker device comprises two high-resolution digital cameras (i.e., sensor resolution: 1600 × 1200; horizontal visual range: 60°; vertical visual degree: 40°) attached to lightweight eyeglasses. The first camera records scenery image with a sampling frequency of 30 Hz. The second monocular eye camera indirectly tracks eye movement by recording the position of the pupil and the corneal reflex via an infrared reflective mirror. Gaze position was recorded via a sequence of frames at a speed of 30 Hz and with an accuracy of 0.5°. A frame was considered valid when it recorded the gaze position in the image scene. The point of gaze was superimposed as a cursor on the scene camera image. Data was transmitted to a portable wireless data transmit unit (DTU) and analysed frame by frame using the ASL EyeVision software. The eye-tracking ratio, as the percentage of success in tracking the point of gaze, was 93.4% (*SD*: 2%). Gaze behaviour was assessed solely during boulder previewing to prevent participants from being impeded by the eye-tracker device while attempting the boulders. Consistent with previous research in the field (e.g., Mitchell et al., 2020; Seifert et al., 2017), we assessed the following eye-tracking metrics: (a) duration of the preview, (b) number of scans, (c) total duration of fixations on climbing holds, (d) fixation duration relative to the previewing time, and (e) applied scan path.

Boulder preview duration refers to the time in seconds that participants spent perceiving the boulders in order to process the visual sensory input and develop an appropriate climbing strategy. The preview duration can thus be considered as response duration of the elapsed time between perceiving the stimulus and generating a response (Mann et al., 2007). As in international competitions, boulder previewing occurred within the 5-min time limit for each boulder, without a separate preview period. This means that participants decided how much time of the 5 min they devoted to previewing the boulder.

The number of scans indicates how many times participants perceived the boulders during the preview. A new scan was retained when participants verbally informed the examiner that they had completed the previous scan and started a new one.

The total fixation duration on climbing holds was assessed to analyse the amount of time participants spent perceiving the holds during the preview. A fixation was defined as the period during which the eye remained stable on the same hold within one degree of movement tolerance for a duration equal to or greater than 120 ms (Catteeuw et al., 2009; Savelsbergh et al., 2005). As the preview duration affects the total duration of fixations (Seifert et al., 2017), we furthermore calculated the relative duration of fixations as a percentage of the preview duration.

Extending Grushko and Leonov (2014) and Seifert et al. (2017), the scan path that participants applied during the preview was determined as a function of their fixations. Specifically, the *linear* scan path was retained when a gradual lateral/upward scan to the finishing hold was recorded following the initial fixation at the starting holds without backward/downward scans. The threshold for backward/downward scans was set at two fixations and 30 cm vertically. The *zigzagging* scan path was retained when gaze moved from side to side, transitioning from one hold to the next to chain hand and foot movements, including sideways/upward and backward/downward fixations (i.e., maximal distance between two fixations was greater than 150 cm and more than two backward/downward fixations). The *sequence of block's* scan path was retained when participants gradually scanned the boulder from the start to the end by splitting it into movement sequences of two to four climbing holds (i.e., distance between two fixations was below 150 cm). Lastly, the *fragmentary* scan path was retained when participants partially perceived the boulder with at least two ignored climbing holds.

2.3.2. Verbal report analyses

To corroborate the eye-tracking metrics (e.g., Hagemann et al., 2006) and gain further insight into the perceptual and cognitive mechanisms involved in boulder previewing, we conducted, following Roca et al. (2013) and Mitchell et al. (2020), post-previewing (immediately after the preview) and post-bouldering (after each attempt at the boulder and at the end of the experiment) interviews that included retrospective think-aloud reports.

In the post-previewing interview, participants were asked in a first question to indicate (no = 0; yes = 1) whether they were able to generate a climbing strategy following the boulder preview. For the second question, they had to indicate the number of climbing movements they were unable to interpret during the preview (e.g., *I was not able to interpret the movement from hold 3 to hold 4*). In the last question of the post-previewing interview, they had to describe their applied scan path (e.g., *I performed an upwards scanning from the starting holds to the finishing hold*).

In the post-bouldering interview, participants had to indicate whether or not failed movement attempts were related to an inappropriate climbing strategy (e.g., *I failed to complete the movement because my climbing strategy was inappropriate*).

2.3.3. Assessment of climbing performances

Video analyses were implemented to assess the participants' climbing performances. By following IFSC regulations, we examined whether they successfully completed the boulders (Top) or reached the zone hold (Zone). A Top was retained when participants achieved the marked finishing hold with both hands and in a controlled position (Hatch & Leonardon, 2023). The Zone consisted of a climbing hold that was relatively easy to grasp, located at the middle of each boulder. Additionally, we assessed the number of failed climbing attempts. A failed climbing attempt was recorded each time the participant fell off the wall. Three bouldering experts (see Design of the Boulders section below) used the video recordings to validate whether the participants' failed climbing attempts were associated with inappropriate climbing strategies (no = 0; yes = 1). As per IFSC regulations, participants had to start each attempt with both hands and in a controlled position on the marked hand- and footholds (Hatch & Leonardon, 2023).

2.4. Design of the boulders

Three bouldering experts (i.e., IRCRA scores: ≥26; years of bouldering experience: ≥15; coaching and route setting qualifications: EQF 4–6) were charged with the setting of the two boulders. To ensure a natural and representative environment, the boulders included diverse climbing movements athletes commonly encounter in daily indoor bouldering (see Figures 1, 2). To investigate the extent to which the preview strategies differ depending on the difficulty of a boulder, boulder 1 had an advanced difficulty level (i.e., IRCRA score: 19). As such, it was theoretically climbable by the advanced and elite climbers, though exceeded the climbing skills of the intermediate climbers. In contrast to boulder 1, boulder 2 had an elite difficulty level (i.e., IRCRA

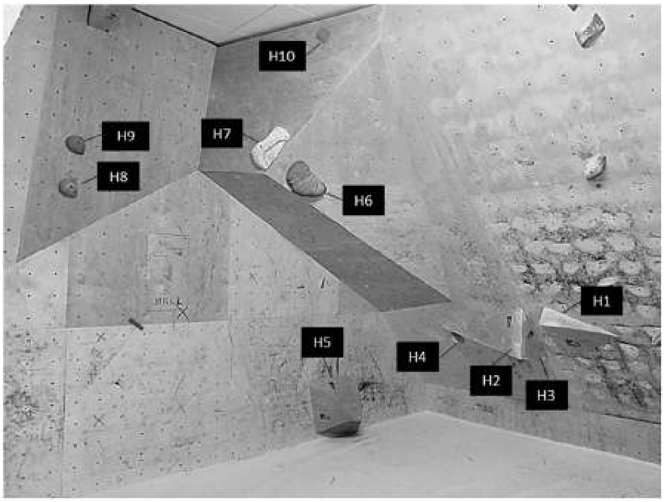

Figure 2. Boulder 2 of the study.

score: 24); that is, it was theoretically climbable by the elite climbers, but exceeded the bouldering skills of the intermediate and advanced climbers (see Fig. 2).

2.5. Statistical analyses

Statistical analyses were conducted using IBM SPSS Statistics 29 (IBM Corporation, USA). Data are presented as mean values and standard deviations ($M \pm SD$) followed by the 95% confidence interval (95% CI), or as percentages. An alpha level of $p < 0.05$ (2-tailed) was used to determine statistical significance. An analysis of variance (ANOVA) was conducted to determine differences of the means between the study groups. A priori power analysis indicated an effect size $\eta^2 = 0.14$ for a sample with 60 participants, three study groups, an α of 0.05, and a power (1-β) of 0.76. All variables were assessed for normality of distribution using the one-sample Kolmogorov-Smirnov test. Levene's test was used to verify the homogeneity of variance. Bonferroni post-hoc pairwise comparisons were calculated to determine between-group differences. The nonparametric Kruskal-Wallis one-way analysis of variance and the Mann-Whitney-U test were used when ANOVA assumptions were violated. Eta-square was calculated and converted to r for indicating the effect size between the groups. Besides categorising climbing skill into ability groups, separate linear regressions were conducted to examine the effect of a dependent variable (e.g., skill level) on predictor variables (e.g., preview duration). Intra-class correlation coefficient and Cohen's kappa were calculated to determine the interrater reliability.

3. Results

3.1. Preview duration and scans (hypothesis 1)

In boulder 1, elite climbers demonstrated shorter preview durations and performed fewer scans than advanced and intermediate climbers (see Table 2). Linear regression analysis revealed a significant relation between the participants' climbing skills (i.e., IRCRA scores) and both the duration of their preview, with $b = -0.10$ (-0.12, -0.07); $R^2 = 0.58$; $F(1, 59) = 79.83$; $p < 0.001$, and the number of scans they performed to process the boulder, with $b = -3.56$ (-4.44, -2.69); $R^2 = 0.53$; $F(1, 59) = 66.39$; $p < 0.001$. Additionally, we observed a significant relation between the participants' years of bouldering and both the duration of their preview, with $b = -0.09$ (-0.12, -0.06); $R^2 = 0.38$; $F(1, 59) = 35.65$; $p < 0.001$, and the number of scans they performed to process the boulder, with $b = -3.28$ (-4.45, -2.12); $R^2 = 0.35$; $F(1, 59) = 31.63$; $p < 0.001$.

Table 2
Visual search behaviour of the study groups during the preview of boulder 1.

Variable (*unit*)	Intermediate (INT)	Advanced (ADV)	Elite (ELI)	Between Groups
Preview duration (*seconds*)	108 ± 14 [102, 115][ADVe†]	74 ± 26 [62, 86][ELIc†]	51 ± 14 [45, 58][INTe†]	$F(2,59) = 80.62$[e†]
Scans (*number*)	2.5 ± 0.5 [2.3, 2.7][ADVd†]	1.5 ± 0.6 [1.2, 1.7][ELIc†]	1.1 ± 0.3 [1.0, 1.2][INTe†]	$H(2) = 36.50$[e†]
Fixation duration (*seconds*)[1]	59.1 ± 12 [53, 65][ADVb]	51.4 ± 16 [44, 59][ELId†]	34.4 ± 11 [30, 41][INTe†]	$F(2,59) = 16.94$[d†]
Fixation-preview (*percent*)[2]	54.6 ± 8 [51, 58][ADVd†]	72.6 ± 13 [66, 79][ELIb]	69.7 ± 13 [64, 76][INTd†]	$F(2,59) = 13.97$[d†]

Note. Results are indicated as $M \pm SD$, followed by the 95% CI in square brackets. Comparisons between two groups are displayed as superscripts characters behind the square brackets, including the group being compared (INT; ADV; ELI), the effect size r (^{a} $r < 0.1$; ^{b}.1 $\leq r < 0.3$; ^{c}.3 $\leq r < 0.5$; ^{d} $0.5 \leq r < 0.7$; ^{e} $r \geq 0.7$), and the symbol † if significant ($p < 0.05$). The last column shows for each item either the ANOVA (F) or the Kruskal-Wallis (H) results, followed by the effect size and the symbol † if significant ($p < 0.05$), indicated as superscripts.
[1] Total duration of visual fixations on climbing holds.
[2] Relative duration of visual fixations on climbing holds indicated as percentages of the preview duration.

Similar to boulder 1, elite climbers demonstrated in boulder 2 shorter preview durations and performed fewer scans than advanced and intermediate climbers (see Table 3). Linear regression analysis revealed again a significant relation between the participants' climbing skills and both the duration of their preview, with $b = -0.09$ (-0.13, -0.06); $R^2 = 0.35$; $F(1,59) = 31.23$; $p < 0.001$, and the number of scans they performed to process the boulder, with $b = -2.47$ (-3.77, -1.17); $R^2 = 0.20$; $F(1,59) = 14.48$; $p < 0.001$. Likewise, we observed a significant relation between the participants' years of bouldering and both the duration of their preview, with $b = -0.11$ (-0.15, -0.06); $R^2 = 0.39$; $F(1, 59) = 36.92$; $p < 0.001$, and the number of scans they performed to process the boulder, with $b = -3.29$ (-4.69, -1.89); $R^2 = 0.28$; $F(1, 59) = 22.03$; $p < 0.001$.

Table 3
Visual search behaviour of the study groups during the preview of boulder 2.

Variable (*unit*)	Intermediate (INT)	Advanced (ADV)	Elite (ELI)	Between Groups
Preview duration (*seconds*)	113 ± 11 [108, 119][ADVb]	104 ± 19 [96, 113][ELId†]	78 ± 24 [66, 89][INTd†]	$F(2, 59) = 20.10$[d†]
Scans (*number*)	2.6 ± 0.5 [2.4, 2.8][ADVa]	2.4 ± 0.6 [2.1, 2.6][ELIc†]	1.8 ± 0.7 [1.5, 2.1][INTd†]	$H(2) = 13.5$[c†]
Fixation duration (*seconds*)[1]	66.2 ± 17 [59, 74][ADVc†]	54.0 ± 11 [49, 59][ELIa]	53.3 ± 16 [46, 61][INTc†]	$F(2,59) = 4.82$[c†]
Fixation-preview (*percent*)[2]	58.6 ± 13 [52, 65][ADVb]	53.9 ± 17 [46, 62][ELIc†]	70.3 ± 14 [64, 77][INTc†]	$F(2,59) = 6.42$[c†]

Note. Results are indicated as $M \pm SD$, followed by the 95% CI in square brackets. Comparisons between two groups are displayed as superscripts characters behind the square brackets, including the group being compared (INT; ADV; ELI), the effect size r (^{a} $r < 0.1$; ^{b}.1 $\leq r < 0.3$; ^{c}.3 $\leq r < 0.5$; ^{d} $0.5 \leq r < 0.7$; ^{e} $r \geq 0.7$), and the symbol † if significant ($p < 0.05$). The last column shows for each item either the ANOVA (F) or the Kruskal-Wallis (H) results, followed by the effect size and the symbol † if significant ($p < 0.05$), indicated as superscripts.
[1] Total duration of visual fixations on climbing holds.
[2] Relative duration of visual fixations on climbing holds indicated as percentages of the preview duration.

3.2. Scan paths (hypothesis 2)

Cohen's k revealed absolute agreement ($k = 1.0$; $p < 0.001$) between the scan paths obtained from the eye-tracker software and the indications participants gave in the post-previewing interviews. Elite climbers (85%) most commonly used the *linear* scan path to preview boulder 1 (see Figure 3). They relied more often on the *linear* scan path than advanced (55%) and intermediate (20%) climbers. Conversely, intermediate climbers most frequently (80%) used the *zigzagging* scan path. They relied more often on the *zigzagging* scan path than advanced (45%) and elite (5%) climbers. Advanced climbers used the *linear* (55%) and *zigzagging* (45%) scan paths equally often. All three study groups made little to no use of the *sequence of blocks* and *fragmentary* scan paths.

In boulder 2 (see Figure 3), elite climbers (60%) used the *linear* scan path more often than advanced (15%) and intermediate (5%) climbers. Conversely, advanced climbers mostly (75%) relied on the *zigzagging* scan path. Furthermore, intermediate climbers used the *fragmentary* scan path (60%) more often than advanced (10%) and elite (0%) climbers. As in boulder 1, none of the participants used the *sequence of blocks* scan path.

3.3. Impact of the difficulty on boulder previewing (hypothesis 3)

Comparisons between the two boulders revealed that the mean preview duration of the three study groups was higher in boulder 2 (98.3 ± 24 s) than in boulder 1 (77.8 ± 30 s; $p < 0.001$; $r = 0.35$). Similarly, elite ($p = 0.001$; $r = 0.55$) and advanced ($p = 0.002$; $r = 0.60$) climbers performed more scans in boulder 2 than boulder 1. While advanced climbers produced shorter preview times and fewer scans in boulder 1 than intermediate climbers, both groups showed comparable data in boulder 2. Further comparisons between the boulders showed that elite climbers applied the *linear* scan path less often in boulder 2 than in boulder 1. Conversely, elite and advanced climbers used in boulder 2 the *zigzagging* scan path more often. However, intermediate climbers used the *zigzagging* scan path in boulder 2 less often than in boulder 1, though referred more often to the *fragmentary* scan path. Lastly, elite and advanced climbers spent in boulder 1 a similar amount of the previewing period fixating the climbing holds. In boulder 2, however, elite climbers spent a higher amount of the previewing period fixating the holds than advanced climbers.

3.4. Reports from the interviews

In the post-previewing interviews of boulder 1, 30% of the intermediate climbers reported being unable to develop a climbing strategy during the preview, while none of the elite and advanced climbers did (i.e., 0%; $p < 0.001$; $r = 0.73$). Similarly, intermediate climbers reported a higher number of climbing movements they were unable to interpret while previewing boulder 1 (2.1 ± 1) compared to advanced (0.4 ± 0.6; $p < 0.001$; $r = 0.67$) and elite (0.1 ± 0.3; $p < 0.001$; $r = 0.74$) climbers. In the post-bouldering interviews, intermediate and advanced climbers reported that 80% of their failed climbing attempts were associated with inappropriate climbing strategies generated during the preview; elite climbers attributed 60% of their failed climbing attempts to inappropriate climbing strategies. The intra-class correlation coefficient ($r > 0.92$; $p < 0.001$) revealed high consistency between the number of failed climbing attempts attributed to inappropriate climbing strategies by the experts and those reported by the participants.

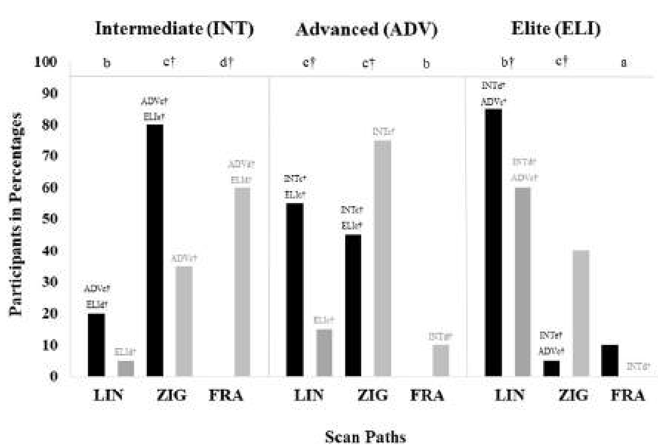

Figure 3. Scan Paths of the Study Groups During the Preview of the two Boulders.

In the post-previewing interviews of boulder 2, 100% of the intermediate and 70% of the advanced climbers stated being unable to generate a climbing strategy during the preview. Elite climbers reported less often (20%) being unable to generate a climbing strategy than advanced ($p = 0.002$; $r = 0.49$) and intermediate ($p < 0.001$; $r = 0.81$) climbers. Similarly, intermediate (2.8 ± 1; $p < 0.001$: $r = 0.80$) and advanced (2.1 ± 1; $p < 0.001$; $r = 0.68$) climbers reported a higher number of climbing movements they were unable to interpret while previewing boulder 2 than elite climbers (0.5 ± 0.7). In the post-bouldering interviews, failed climbing attempts associated with inappropriate climbing strategies generated during the preview were reported in 65% of cases for elite climbers, 75% for advanced climbers, and 45% for intermediate climbers. The intra-class correlation coefficient ($r > 0.90$; $p < 0.001$) revealed, again, high consistency between the number of failed climbing attempts attributed to inappropriate climbing strategies by the experts and those reported by the participants.

3.5. Climbing performances

Elite climbers (85%) were more successful at completing boulder 1 (i.e., Tops) than advanced (40%; $p = 0.014$; $r = 0.46$) and intermediate (10%; $p < 0.001$; $r = 0.74$). Additionally, advanced climbers (90%; $p = 0.031$; $r = 0.34$) produced a higher number of Zones than intermediate climbers (60%). Elite climbers performed fewer failed climbing attempts (2.5 ± 1) than advanced (4.7 ± 2; $p = 0.031$; $r = 0.57$) and intermediate (8.6 ± 4; $p < 0.001$; $r = 0.72$). Linear regression analysis revealed a significant relation between the participants' number of failed climbing attempts and both their self-perceived ability to generate a climbing strategy, with $b = -5.67$ (−7.41, −3.92); $R^2 = 0.42$; $F(1, 59) = 42.30$; $p < 0.001$, and the number of climbing movements they were unable to interpret during the preview, with $b = 1.94$ (1.28, 2.61); $R^2 = 0.37$; $F(1, 59) = 34.21$; $p < 0.001$.

Sixty five percent of the elite climbers successfully completed boulder 2, with no Tops in the advanced and intermediate groups ($p < 0.001$; $r = 0.68$). As per boulder 1, advanced climbers (55%) produced a higher number of Zones than intermediate climbers (0%; $p < 0.001$; $r = 0.61$). Elite climbers performed fewer failed climbing attempts (2.3 ± 2) than advanced (6.5 ± 2; $p < 0.001$; $r = 0.73$) and intermediate (9.6 ± 3; $p < 0.001$; $r = 0.82$). Linear regression analysis revealed a significant relation between the participants' failed climbing attempts and both their self-perceived ability to generate a climbing strategy, with $b = -5.55$ (−6.93, −4.16); $R^2 = 0.53$; $F(1,59) = 64.31$; $p < 0.001$, and the number of climbing movements they were unable to interpret during the preview, with $b = 1.97$ (1.46, 2.48); $R^2 = 0.50$; $F(1,59) = 58.96$; $p < 0.001$.

4. Discussion

The present study aimed at providing compelling insights into critical perceptual and cognitive mechanisms underlying superior cognitive-motor performance in the Olympic discipline of bouldering. Extending previous research on neural efficiency, we investigated cognitive-behavioural processes in climbers of varying skill levels by analysing their gaze behaviour and self-reported climbing strategies during the previewing of two boulders of different difficulty. Findings revealed a significant relation between climbers' skill levels and their preview duration, as well as their number of scans during previewing. In addition to preview duration and number of scans, elite climbers more commonly used the *linear* scan path than advanced and intermediate climbers to preview the boulders. Comparisons between the two boulders also revealed that elite and advanced climbers required longer preview durations, performed more scans, and referred to the *zigzagging scan path* more often when processing the climbing movements of the more difficult boulder 2. Overall, findings revealed that cognitive-behavioural processes during route previewing are not only related to climbing expertise, but also substantially dependent on the difficulty of boulders.

4.1. Preview duration and scans (hypothesis 1)

The findings that elite climbers produced in both boulders shorter preview durations and fewer scans than advanced and intermediate climbers imply that more accomplished climbers required less time to process visual sensory input during previewing. These results confirm hypothesis 1 and are consistent with findings reported by Medernach and Memmert (2021), who observed shorter previewing times in advanced climbers compared to intermediate and novice climbers. Drawing on climbing literature, experts' shorter processing times could be associated with their extensive repertoire of climbing movements (Sanchez et al., 2019), coupled with their superior perceptual judgement of climbing capabilities (Whitaker et al., 2019). Longer sport-specific practice and higher self-reported previewing skills support the assumption of a more comprehensive movement repertoire among elite climbers, although self-assessments should be interpreted with caution. Similar to other sports (see Cowell et al., 2019; Roca & Williams, 2016, domain-specific movement patterns stored in long-term memory help climbers to decode sensory information and explore potential climbing strategies (Medernach & Memmert, 2021; Sanchez et al., 2019). This may account for the faster development of climbing strategies among experts. The significant relation between climbers' skill levels and both preview duration and number of scans endorses the expertise-processing-paradigm in boulder previewing – the more experienced climbers are, the less time they need to process sensory input during the preparatory period.

4.2. Scan paths (hypothesis 2)

Findings revealed that elite climbers used the *linear* scan path more often than advanced and intermediate climbers during the previewing of the two boulders. In their work on visual strategies in exploring climbing routes, Grushko and Leonov (2014) originally defined the *ascending* scan path as the upward scanning of climbing routes without in-depth movement analysis. The authors proposed that climbers rely on the *ascending* strategy to preview easy routes or familiar climbing movements. Extending Grushko and Leonov's (2014) work to bouldering, the prevalent use of the *linear* scan path among elite climbers, in combination with shorter preview durations and fewer scans, suggests that experienced climbers tend to rely more often on a superficial scanning when previewing boulders, thus confirming our hypothesis 2. While this finding supports the expertise-processing-paradigm assumption, the prevailing use of the *linear* scanning strategy does not elucidate why experts confined themselves to a more fleeting previewing. Our findings may be attributed to the fact that superior technical and motor skills made a functional examination of climbing movements and a thorough scanning of relevant features less critical for experts to successfully execute motor actions and thus ascent the boulders. However, considering the difficulty of the boulders (i.e., close or similar to the level of elite climbers), it is more likely that experts' domain-specific expertise allowed them to quickly perceive functional strategies and promptly understand how to chain action in sequences.

Grushko and Leonov (2014) furthermore assumed that climbers use the *zigzagging* scanning strategy when they can quickly chain hand and foot actions. Our results partly disagree with Grushko and Leonov's assumption that climbers rely on this strategy when the interpretation of visual cues is less challenging. Firstly, because elite climbers almost entirely eschewed the *zigzagging* strategy in the easier boulder 1, and secondly, because elite and advanced climbers resorted to the *zigzagging* strategy more often in the more difficult boulder (boulder 2). Given that the *zigzagging* scanning strategy comprises the transitioning from one hold to the next, this strategy may enable climbers to pick-up functional aspects and identify opportunities for action, as proposed by Seifert et al. (2017). Based on our findings, we therefore assume that climbers tend to the *zigzagging* strategy when they have to preview tasks that roughly correspond to their level of difficulty.

According to our findings, particularly inexperienced climbers tend to use the *fragmentary* scan path when previewing boulders. Grushko and Leonov (2014) defined the *fragmentary* scanning as a strategy in which climbers partially perceive routes and ignore climbing holds while previewing them. Extending Medernach and Memmert (2021), such partial processing of visual input among intermediate climbers was probably because they were overwhelmed with processing visual sensory input; insufficient climbing skills in combination with boulder difficulty may have impeded them from perceiving functional strategies and chaining motor actions; however, 10% of the elite climbers chose the *fragmentary* scan path when previewing the easier boulder (boulder 1). As such, climbers might not only rely on partial processing of bouldering tasks when difficulty exceeds their skill level, but also when difficulty is considerably below their skill level. That would make functional examination of climbing movements less critical for boulder completion.

Lastly, it is worth noting that none of the climbers in our study performed a *sequence-of-blocks* scan path, contrary to previous findings in sport climbing (e.g., Grushko & Leonov, 2014; Seifert et al., 2017). Grushko and Leonov (2014) originally defined this scanning strategy as in-depth visual processing by gradually perceiving the route and splitting it into sequences of two to four climbing holds. While this strategy appears to be a promising approach for previewing climbing routes that are considerably longer than boulders, splitting a boulder with an average of four to eight climbing holds into different sub-sequences may only be applicable to given boulders. That is, the design of the boulders (e.g., types of movement) and the characteristics of the bouldering walls (e.g., height) in our study may account for the findings on the *sequence-of-blocks* scan path, making further research imperative to fully understand the scan paths used in bouldering.

4.3. Impact of the difficulty on boulder previewing (hypothesis 3)

Besides their lower sport-specific expertise, intermediate climbers' longer previewing times and higher number of scans are also likely to be related to the difficulty of the given boulders. Climbing performance results confirm that both boulders were considerably beyond the skill level of intermediate participants; although, it should be considered that post-previewing questions present a limitation in our study, as they could potentially have influenced subsequent climbing performance. Our assumption that cognitive-behavioural processes during route previewing are also substantially associated with boulder difficulty is furthermore supported by the previewing behaviour of advanced climbers. For instance, in boulder 1, which matched the skill level of the advanced group, advanced climbers had shorter previewing times and fewer scans than intermediate climbers. However, in boulder 2 (of higher difficulty level for both advanced and intermediate climbers – none were able to climb it), climbers from both groups produced comparable previewing times and a similar number of scans. Similarly, we also observed that advanced and elite climbers required longer previewing times and performed more scans in the more difficult boulder (boulder 2), even though both boulders included an equal number of climbing holds and similar climbing movements.

Altogether, longer previewing times, a higher number of scans, and more in-depth scanning paths confirm our hypothesis 3 that cognitive-behavioural processes during route previewing are closely associated with boulder difficulty. Naturally, climbers who preview boulders with a difficulty close to, or exceeding their skill level risk being overwhelmed with the interpretation of visual sensory input and the development of climbing strategies (Medernach & Memmert, 2021); they risk being hindered from perceiving functional strategies and thus chaining motor actions, which accounts for longer processing times for decoding climbing movements.

Previous research in climbing supports the assumption that boulder difficulty relative to the climber's skill considerably influences cognitive-behavioural processes during previewing. As an example, Bläsing et al. (2014) examined the impact of climbing level on cognitive activation of grasping actions, and found that climbers exhibited associated grasping postures when perceiving different climbing holds, while non-climbers did not. Moreover, Pezzulo et al. (2010) observed that expert climbers showed a more accurate recall of climbing holds than beginners after previewing a route that matched their skill level. However, this perceptual-cognitive advantage dissipated in routes that corresponded, or considerably exceeded skill level of both groups. The authors argued that embodied motor simulations are essential to mentally simulate climbing movements and thus perceive climbing opportunities. That is, if climbers do not possess motor expertise to climb a route, then they are also more likely to be unable to mentally simulate the climbing movements. Reports from the post-previewing interviews substantiate this assumption, as intermediate climbers stated more often that they were unable to generate climbing strategies and interpret the climbing movements than advanced and elite climbers.

5. General conclusion

This study provided relevant insights into perceptual and cognitive mechanisms underlying superior cognitive-motor performance in the Olympic discipline of bouldering. Findings revealed that boulder difficulty and climber's skill level influence preview duration, number of scans, and applied scanning strategy during previewing. Both, climbing movement repertoire developed through long-term deliberate practice and appropriate perceptual judgement of climbing capabilities account for the expertise-processing-paradigm in boulder previewing. Domain-specific knowledge is critical for decoding sensory input, picking-up functional aspects, and identifying opportunities for action. Although we did not directly examine the relationship between gaze behaviour and brain activity, findings from the present study offer complementary insights reinforcing the neural efficiency hypothesis and the associated motor skill automaticity originally proposed by Fitts and Posner (1967). While processing boulders in the initial cognitive stage requires high cognitive effort and explicit knowledge, such processing becomes increasingly automatised in the autonomous stage, requiring less conscious effort and allowing individuals to focus on task-specific details (Price et al., 2009). That is, high attentional demands and limitations of human processing capacity (Cowan, 2008) may account for longer preview durations, more scans, and different scanning strategies among less-experienced climbers. Conversely, superior task-specific cognitive proficiency among experts seems to contribute to a more efficient recruitment and utilisation of cortical resources (Babiloni et al., 2010; Del Percio et al., 2009), with plastic changes occurring in neuronal structures involved in movement planning and execution control (Hatfield, 2018; Lohse et al., 2014). Experts appear to initially exhibit greater functional activation of visuospatial attention, followed by inhibition of nonessential cognitive interference to motor processes (Wang et al., 2020); this could account for a more prompt and conscious pickup of perceptual cues (e.g., Roca & Williams, 2016; Williams & Jackson, 2019), more efficient visual search strategies (e.g., Ericsson, 2017; Mann et al., 2007), and a better identification of representative patterns (e.g., Roca & Williams, 2016; Smeeton et al., 2004).

CRediT authorship contribution statement

Jerry Prosper Medernach: Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xavier Sanchez:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Julian Henz:** Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Memmert:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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