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Learning and transfer of perceptual-motor skill: Relationship with gaze and behavioral exploration

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Abstract

Visual and haptic exploration were shown to be central modes of exploration in the development of locomotion. However, it is unclear how learning affects these modes of exploration in locomotor task such as climbing. The first aim of this study was to investigate the modifications of learners' exploratory activity during the acquisition of a perceptual-motor skill. The second aim was to determine to what extent the acquired perceptual-motor skill and the learners' exploratory activity were transferred to environments presenting novel properties. Seven participants attended 10 learning sessions on wall climbing. The effects of practice were assessed during pretest, posttest, and retention tests, each composed of four climbing routes: the route climbed during the learning sessions and three transfer routes. The transfer routes were designed by manipulating either the distance between handholds, the orientation of the handholds or the handholds shape. The results showed that the number of exploratory hand movements and fixations decreased with practice on the learning route. A visual entropy measure suggested that the gaze path in this route became more goal-directed on posttest, but some search was necessary on the retention test. The number of exploratory movements also decreased on the three transfer routes following practice, whereas the number of fixations was higher than on the learning route, suggesting that, with learning, participants relied more on exploration from a distance to adapt to the new properties of the transfer routes. Analyses of the individual performances and behaviors showed differences in the development of skilled exploratory activity.

Keywords Visual perception · Entropy · Affordance · Adaptability · Skill acquisition

Throughout practice, learners discover what they can do and how they can do it to successfully reach their task-goal. According to the ecological approach to perception and action, as learners practice, they attune to relevant information for actions that, when it is scaled to their action capabilities and body size, enables them to accurately perceive opportunities for action, also called affordances (Fajen, 2007; Gibson, 2015). Yet information has to be generated and picked up actively by the perceptual systems through changes in the body orientation, movements of the eyes, surfaces touching, and so on (Gibson, 1966). This exploratory activity produces information that is used to guide the individual's action (Gibson, 1966, 2015). In this view, exploratory activity links the information to the control of movements (Gibson, 2015; Reed, 1996). It is conceived as a skill that is learned as individuals get better at discriminating their surroundings (Gibson, 1966; Gibson & Gibson, 1955). Thus, the adaptive control of movements requires (i) adequate exploratory actions and (ii) differentiation of the relevant information structures (Adolph et al., 2000; Adolph et al., 2001). In the present study, we used a climbing task to investigate how individuals change their exploratory activity as they learn to exploit the properties of their learning environment (i.e., the holds on the climbing wall) and to examine to what extent these changes can be transferred to environments presenting novel properties.

Changes in visual and haptic exploration in climbing and locomotor tasks

In studies about perceptual-motor control and learning in climbing (Nieuwenhuys et al., 2008; Orth et al., 2018a;

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Pijpers et al., 2005; Pijpers et al., 2006; Seifert et al., 2018) and about the broader topic of the development of locomotion (Adolph & Franchak, 2017; Franchak et al., 2011; Kretch & Adolph, 2017), visual and haptic exploration have been investigated as key modes of exploration for finding affordances. In climbing studies, climbers use exploratory hand movements to better perceive (i) whether a handhold is within reaching distance and (ii) how to best grasp the handhold (Orth et al., 2018b; Pijpers et al., 2006; Seifert et al., 2018). Haptic exploration of a handhold is an engaging modality because the climbers have to free one limb that would normally be used as a support. However, haptic information also informs and reassures them about how the hand and body should be placed and helps them to simulate a grasping pattern for using the handhold as a support. Recent studies have shown that climbers perform exploratory hand movements less frequently as they attune to the affordances of the holds with practice, and that less experienced climbers rely more than skilled climbers on exploratory hand movements even when they are discovering a new route (Orth et al. 2018b; Seifert et al., 2018). These results suggest that with experience and practice, the information obtained from a distance using the visual system becomes sufficient for climbers to perceive and chain their movements on the route. Only one study investigated the changes in the gaze behavior of climbers during practice (Button et al., 2018), showing that they performed fewer fixations during the ascents over the six trials of the protocol, although they maintained their search rate (i.e., the number of fixations per seconds; Button et al., 2018). Yet no study has investigated the effect of practice on both hand movements and gaze behaviors in climbing. A joint analysis of the two was only performed in a study designed to assess the effect of anxiety on the exploratory activity during a climbing task (Nieuwenhuys et al., 2008). It revealed that the anxiety induced by an increase in climbing height drove the climbers to less efficient climbing behavior, which was suggested by the increase in exploratory hand movements, longer grasps on the handholds, and longer fixation durations. Also, this study showed that the fixations occurring during hand movements (categorized as performatory fixations) had mean durations that were about three times longer than the other fixations (categorized as exploratory fixations) but that the exploratory fixations were about two times more frequent than those that were performatory. These results indicate that when climbers are looking for information about affordances, either in the first learning sessions or in anxiety conditions, they display high exploratory activity, but as they better attune to the affordances of the climbing routes, this exploratory activity tends to decrease and exploratory hand movements even seem to disappear.

In developmental psychology, studies have shown that children also prefer touch and vision as they search for ways to match locomotor actions with a bridge or a slope (Adolph, 1995, 2008; Adolph et al., 2000). The results of these studies led to the ramping-up hypothesis to describe the organization of exploratory actions (Kretch & Adolph, 2017). According to this hypothesis, modes of exploration are organized in space and time so that individuals progressively use more engaging modes to perceive whether and how to cope with an obstacle (e.g., a bridge or a slope). Visual exploration is usually the first modality used for information pickup, and if the information is insufficient, haptic information may be sought. The children in Kretch and Adolph' (2017) study used exploratory touch (with hands or feet) to confirm the visual information (e.g., regarding bridge width) or to obtain information that was not available from a distance (e.g., information about ground rigidity or surface). However, neither the mode (visual or haptic) nor the quantity (number of actions and durations) of explorations predicted task success, although experience with the task did (Kretch & Adolph, 2017). For example, these children required experience with the mode of locomotion to better use the picked-up information and improve decision-making. The children with less experience used touch in both safe and unsafe (e.g., wide and narrow bridge) conditions, demonstrating (i) their difficulty in exploiting both visual and haptic information and (ii) a lack of sensitivity to their action capabilities (Kretch & Adolph, 2017). Overall, these results show that the number and/or duration of exploratory actions decrease with learning and development, and thus that the search for information declines. It also suggests that as individuals better differentiate information and become more sensitive to their action capabilities, they become more skilled at accurately revealing opportunities for action in their environment.

These results in studies about climbing and the development of locomotion suggest that two functions of exploratory activity can be discerned and applied to skill learning. The first function is to search for and discover available information so that the learners progressively differentiate the relevant information for task completion (Gibson, 2000; Gibson & Gibson, 1955). This function of exploratory activity can thus be characterized by a high amount of actions of the perceptual systems as the learners discover the properties of their task environment and the possibilities for action that they afford (Gibson, 1966). Such exploratory activity can appear to lack in goal-directedness because the learners may attend to many areas in the environment (e.g., with touch or visual search), but this is necessary to progressively raise new possibilities for action and reorganize the information-movement coupling more specifically to the constraints of the task environment (Adolph & Robinson, 2015; van Dijk & Bongers, 2014).

The second function of the exploratory activity appears with experience in the task and is used to effectively reveal, pick up, and exploit information for affordances (van Dijk & Bongers, 2014). Although the learners are now attuned to the possibilities for action that their task environment offers, they still have to continuously scale their movements to the unfolding dynamics of their relation with this environment. This process is called calibration (Davids et al., 2012; Fajen et al., 2008) and has been suggested to be characterized by a gain in the goal-directedness of the exploratory activity. Essentially, the primary role of the exploratory activity is now to reveal and exploit relevant information for task achievement, whereas the discovery role of the exploratory activity predominated at the earlier learning stage (van Dijk & Bongers, 2014). Therefore, in the present study, we want to examine whether this assumption can be observed when learning a climbing task. That is, learners' exploratory activity should not be only characterized by a decrease in the amount of exploratory actions, but it should also reorganize so that their exploratory activity becomes better embedded in the continuous flow of actions by gaining in goal-directedness.

Transfer of learning in ecological psychology

With learning, exploratory activity should become a skill by enabling individuals to probe and exploit relevant information in different environmental contexts to adapt their behavior accordingly (Adolph, 2008; Gibson, 1966). The second question raised in this paper is to what extent can climbers transfer their perceptual-motor skill and exploratory activity to an environment with different properties (i.e., a different climbing route)?

In ecological psychology, the transfer of learning implies the transfer of both attunement and calibration to the new context. The transfer of attunement, has been presented as the ability to detect information with different action systems (de Vries et al., 2015) or as the ability to detect and exploit reliable information to guide action in different contexts of performance (Huet et al., 2011; Smeeton et al., 2013; Smith et al., 2001). For example, in a tennis anticipation task, the participants trained to attend to reliable informational movement patterns of a stick-figure player's shot. They were able to transfer their ability to anticipate the direction of the shot even in conditions where the informational movement patterns on which they had focused their training (the arm and racket movement of the stick figures) were neutralized, with only other body region movements remaining available (Smeeton et al., 2013). The conclusion was that when the learners' attention during practice was directed toward reliable information, this attunement facilitated the transfer of the perceptual motor skill to new contexts, even when the available information was less reliable.

The transfer of calibration has been studied through two processes (Brand & de Oliveira, 2017). The first is called recalibration and refers to the rearrangement of the perception-action coupling (i.e., the rescaling of information) following a disturbance that makes the coupling inaccurate. The perceptual-motor system needs to be recalibrated when (i) an individual's action capabilities or body dimension changes over short (e.g., by wearing an apparatus like ankle weights or walking on stilts) or longer (e.g., with development or training) timescales or (ii) perception is altered (e.g., by wearing prism glasses). The second process is the transfer of calibration, which occurs when the rearrangement of the perception-action coupling in one action transfers to another action. For example, although children are able to perceive the cross-ability of a slope when they crawl, when they start walking, they will engage in walking on impossible slopes unless they have sufficient experience with this new mode of locomotion (Adolph et al., 2008; Kretch & Adolph, 2013). These findings suggested that the transfer of calibration was possible only when the children were sensitive to the boundaries of their action capabilities in the new mode of locomotion. Brand and de Oliveira (2017), noted that recalibration and transfer of calibration required exploratory activity that was effective only if (i) the individuals were attuned to the relevant information, (ii) the source of information was still available after disturbance, and (iii) the perceptual-motor skill had been thoroughly learned.

In sum, the attunement of the perceptual-motor system to reliable information appears to be a prerequisite for any form of transfer of learning from one context to another. Then, if this prerequisite is respected, the quantity of exploratory activity necessary to adapt the actions to the new context depends on the intensity and nature of the disturbance.

Current study

An indoor climbing task was chosen for this study. Climbers need to learn a route-finding skill. That is, they have to perceive how to use the holds on the climbing route so that they limit the movements of their center of mass during ascents and chain their climbing movements fluently (Cordier et al., 1994; Seifert et al., 2018). Route-finding skill highlights a particularity of climbing, which is that perceiving an opportunity for action on the route depends on the climber's previous action. For example, grasping a handhold affects the availability of a limb for the next movement, and handhold orientation affects the entire body posture (Seifert et al., 2015). This illustrates how nested the affordances in climbing tasks are, as the perception of one action during the ascent is accurate if the climbers also perceive the changes in their action capabilities due to the previous action (Wagman et al., 2018; Wagman & Morgan, 2010). Essentially, if the properties of the climbing route are changed, it may affect the whole chain of movement. For this reason, acquiring exploratory skill that can be transferred and used to perceive how to chain movements on new routes is quite valuable in lead climbing and bouldering, two of the three competitive indoor climbing disciplines where performers are often confronted with new climbing routes.

As indoor climbing tasks allow the manipulation of environmental properties that directly impact the locomotion of climbers (Orth et al., 2016; Seifert et al., 2015), the transfer of route-finding skill can be assessed by changing the environmental properties of the learning route. More specifically, the literature has shown that climbers need to adapt differently according to the changes: (i) increasing the distances between handholds requires more force and amplitude in the climbing movements (Testa et al., 1999), (ii) changing the handhold orientation requires a modification in the whole body posture to use the handholds (Seifert et al., 2015), and (iii) changing the handhold shape requires different grasping patterns and close attunement to the functional properties of the handholds (Button et al., 2018).

Regarding our study objectives, we first hypothesized that the participants would learn how to pick up and exploit relevant information for action on the learning route through attunement and calibration of their perceptual-motor system, while they discovered climbing movements that fit both the route properties and their action capabilities. Their enhanced route-finding skill (i.e., their ability to perceive and chain climbing movements) would lead to greater climbing fluency (i.e., lower entropy of hip displacement), while the ability to explore efficiently would be revealed by (i) a decrease in the quantity of exploratory actions (i.e., fewer exploratory hand movements and a decrease in the gaze search rate) and (ii) more goal-directed gaze behavior (i.e., lower visual entropy) as exploration would be increasingly used to guide actions rather than searching for affordances.

The second hypothesis was that, the transfer of route-finding skill to routes with modified properties would be revealed by similar improvements in the fluency scores on the learning and transfer routes (i.e., similar decreases in the entropy of the hip displacement in the posttest). The transfer of exploratory skill would also be revealed by similar changes in gaze and haptic behaviors on the learning and transfer routes. We expected that learners would show better transfer when the new properties of the climbing route invite learners to adapt their climbing movements with low-order behavioral changes (i.e., superficial refinement at spatial or temporal level, like amplitude of movement), than when the new properties invite high-order behavioral changes (i.e., deep reorganization at the motor coordination level, like postural regulation and coordination between limbs) as the disturbance of the information-movement couplings would be more important in the latter condition.

Method

Participants

Eight students volunteered to participate in the study, but one dropped out after the first learning session. The remaining seven participants (two males and five females, mean age 18.4 ± 0.8 years old, mean height 167.7 ± 5.3 cm, mean weight 57.4 ± 5.7 kg, mean arm span 165.2 ± 7.6 cm) had a grade 5C skill level in rock climbing on the French Rating Scale of Difficulty (F-RSD), which corresponds to an intermediate level (Draper et al., 2015). They had been climbing for about 2 years for 3 hours per week. All had normal or corrected-to-normal vision.

Protocol

The learning protocol consisted of 13 climbing sessions. Ten of them were learning sessions during which the participants always climbed the same route, which was the Control route. They had three trials per learning session and their task-goal was to "*find the way to climb the route as fluently as possible, avoiding pauses and saccades.*" After each learning session, they received feedback on their hip trajectories and fluency scores.[1] The learning sessions were distributed over 5 weeks, with two climbing sessions per week. Participants also attended three test sessions: a pretest before the start of the learning sessions, a posttest the week following the learning sessions, and a retention test 5 weeks after the posttest. During the test sessions, they had to climb four routes in random order. One of them was the Control route and the three others were transfer routes. The transfer routes had the same number of handholds as the Control route (i.e., 16), but they differed on half the handholds as follows: (i) the distance between handholds was increased but remained less than the

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[1] The feedback was designed to give participants information about their climbs' outcomes and to guide learning. The aim was to encourage the participants to explore new ways to climb the route and fluently chain their movements to lower the fluency scores as much as possible without explicitly telling them how to improve. Thus, we encourage with this feedback an external focus of attention (Peh et al., 2011; Wulf & Shea, 2002). More specifically, participants received by email the feedback with pictures of the harness light trajectories on the three climbs of the session (one picture/climb) and the corresponding values of three fluency indicators labeled as spatial, temporal and spatiotemporal fluency. On the second session, the feedback of the first session was described and explained to the participants. They were told that the line corresponded to the trajectory of the light on their harness during the climb and that the more direct the trajectory is, the better (i.e., the lower) the spatial fluency score would be (the geometric index of entropy; Cordier et al., 1994). The temporal fluency score was described as the percentage of the climbing time spent immobile (Orth et al., 2018) and the spatiotemporal score (the jerk of hip rotation; Seifert et al., 2014) as the amount of saccadic movements during the climb. They were also told that their aim is to lower these scores as much as possible throughout the practice sessions. Before each session, the experimenter asked the participant if they received and looked at the last feedback, and if they did not, the experimenter showed the feedback before starting the new session.

participants' arm span, (ii) the handhold orientation was changed (i.e., it turned 90°), or (iii) the handhold shape was changed. The manipulations are illustrated in Fig. 1. The three transfer routes were respectively termed the Distance route, the Orientation route, and the Shape route. As shown in Fig. 2, the Control route was divided into four areas composed of four handholds and the modifications to create the transfer routes were located in two of these areas: the Distance route differed in Areas 1 and 4, the Orientation route in Areas 2 and 4, and the Shape route in Areas 1 and 2. Two qualified route-setters rated the four routes as 5B+ on the F-RSD (Draper et al., 2015), which indicated slightly under but close to maximal difficulty for the participants. All the climbs were top-roped, which meant that the safety rope was anchored at the top of the climbing wall. This safety mode was chosen as an attempt to reduce the potential effects of higher anxiety during ascents (Hodgson et al., 2009). Before each trial for all sessions, the participants had 2 minutes to preview the route.

Measurement of performance and exploratory hand movements

On each ascent, the participants wore a harness with a light placed on the back. Ascents were filmed at 24 fps on 1920 × 1080 pixel frames with a GoPro Hero 3 camera covering the entire route from 5.45 m and at a height of 5 m. The harness light was tracked on video with Kinovea 0.8.25 software to obtain coordinates of hip trajectory projection on the 2D wall. The camera lens distortion was compensated by importing the intrinsic parameters of the camera, and the video perspective was corrected using a manually set grid-based calibration on this software. The videos of the climbs were also used to code the exploratory hand movements of the participants (see the subsection Exploratory Hand Movements in the section Dependent Measures for more details).

At the beginning of each trial, the participant stayed immobile, with two hands on the first handhold and one foot on the first foothold. The start of the trial began when the second foot left the ground. The trial ended when the participants held the last handhold with their two hands.

Measurement of gaze behavior

Although visual exploratory activity is not limited to eye movements, we chose to investigate the participants' visual exploration through their gaze behaviors measured with a mobile eye-tracking system. In our climbing task, their head or body movements were not limited. In such conditions, the gaze locations obtained with the mobile eye-tracking system reflect the visual exploratory activity that resulted from the participants' eye, head and body movements (Franchak, 2019).

On each ascent, the climbers wore SMI eye tracking glasses (SensoMotoric Instruments GmbH, Teltow, Germany) that recorded gaze behavior at 60 Hz. This binocular system is reported to have an accuracy of 0.5° of visual angle (https://imotions.com/hardware/smi-eye-tracking-glasses/; see also Cognolato et al., 2018, for a comparison

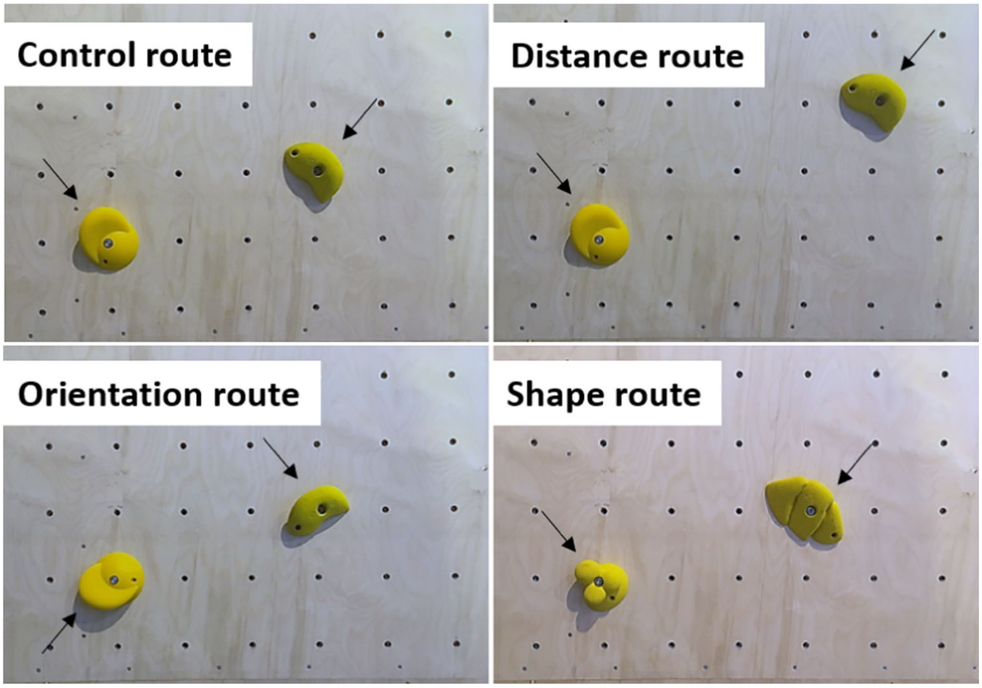

Fig. 1 Manipulation of the handholds to create the transfer routes. The arrows indicate the preferential grasping enabled by the handhold

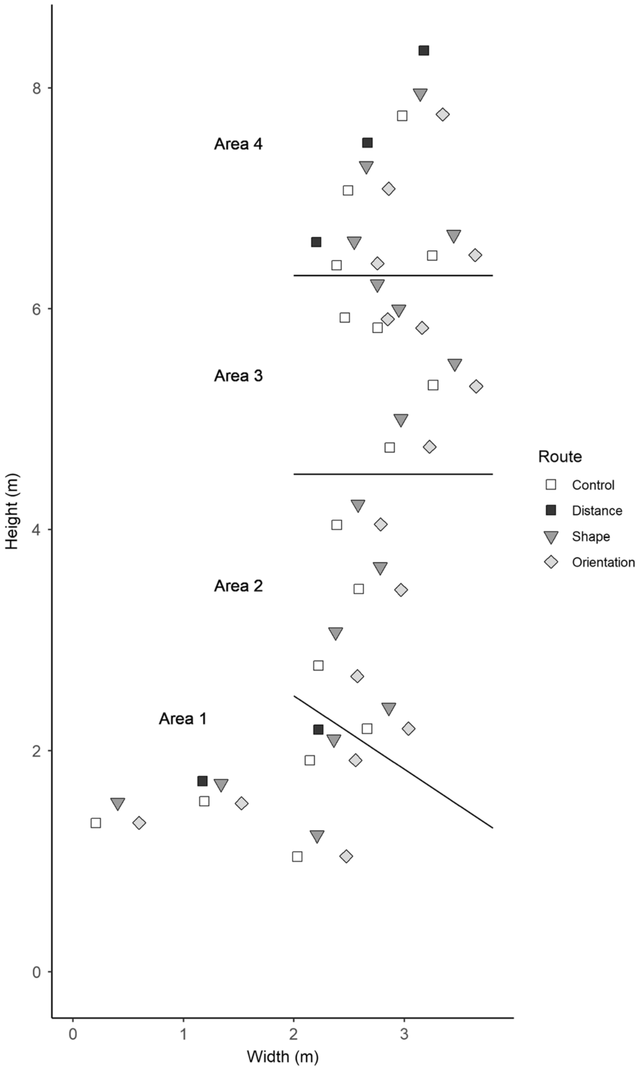

Fig. 2 Location of the handholds for the four routes in the test sessions. The shapes and colors refer to the four routes climbed during the test sessions. Only the five handholds of the Distance route that were moved are visible because the other handholds share the same locations as the handholds of the Control route

with other eye-tracking system). It needs a three-point-based calibration, which was performed before each trial. To mark the beginning of each trial, the participant had to fixate on a target at the start of the route placed above the first handhold. The end was assumed when the participants fixated the last target placed above the last handhold.

Eye fixation locations on the wall were obtained with the eye-tracking analysis software, SMI BeGaze (Version 3.7.59, SensoMotoric Instruments GmbH, Teltow, Germany). Fixation events were determined with the SMI Event detection algorithm as periods during which the point of regard velocity was (i) below 8°/s or (ii) below 100°/s and the velocity skewness (i.e., the ratio between the velocity mean and median over a 5-sample window) was below a value of 5. In addition, fixation events that lasted less than 50 ms were not considered. Then, we classified each fixation location into a specific area of interest (i.e., AOI). A 20-cm circle around each hold of the climbed route was considered as an AOI of the route and the rest as the last AOI (i.e., the wall).

Dependent measures

Performance The coordinates of the hip trajectory were used to compute the geometric index of entropy (i.e., GIE), which assesses the complexity of the hip trajectory (Cordier et al., 1994). GIE was designed as a global measure of performance that reflects the degree of coherence in perception-action couplings (Cordier et al., 1994). Using the length L of the hip trajectory and the perimeter c of the convex hull around the trajectory, GIE (H) is calculated with the following equation:

$$H = \log_2\left(\frac{2L}{c}\right). \qquad (1)$$

Therefore, a low GIE reflects a smooth hip trajectory, indicating that the climber is sensitive to the environmental constraints, whereas a high GIE reveals a random trajectory that might be linked to the need to search the environment in order to keep progressing on the route.

Exploratory hand movements The number of exploratory hand movements was counted by an expert climber for each trial of the test sessions. The expert climber watched the videos captured with the GoPro camera and coded the number of exploratory movements and the corresponding handholds on an Excel sheet. In accordance with Pijpers et al. (2006), an exploratory movement was defined as a participant's hand touching or grasping a handhold without using it to progress on the route.

Gaze behaviors In order to assess the quality of the gaze-tracking data, the percentage of samples captured during the climbs was measured for each trial. Thus, the measured tracking ratio corresponded exactly to the period used to investigate the participants' gaze behaviors.

The gaze behaviors were assessed with three commonly used search rate measures: (i) the mean duration of fixations, (ii) the number of fixations, and (iii) the number of AOI fixated during each ascent (Dicks et al., 2010; Vaeyens et al., 2007). In addition, we calculated the relative duration of fixations on AOI, which was the total duration of fixations on climbing holds divided by the total duration of fixations on the trial. This quantified the gaze behavior related to AOI as the participants searched for holds on the wall while climbing the new routes. These four measures were also used to better understand the relative visual entropy measure as its function is still under debate (for more detail, see the review of Shiferaw et al., 2019).

The relative visual entropy was calculated to assess the degree of uncertainty in the spatial pattern of participants' fixations during ascents (Shiferaw et al., 2019). Based on the classification of AOI, a sequence of visited AOI was created, and the probability of looking at each AOI was computed (*p(i)*, *i* is an AOI). A transition matrix was created based on the sequence of visited AOI during the ascent and this matrix was converted into a probability matrix that gave the probability of transitioning from one AOI to another (*p(i,j)*, the probability of shifting from *i* to *j*) in each cell. Then, we computed the observed visual entropy with the following equation (Ellis & Stark, 1986):

$$H_{Observed} = -\sum_{i=1}^{n} p(i)\left[\sum_{j=1}^{n} p(i,j)\log_2 p(i,j)\right], i \neq j. \qquad (2)$$

This value was divided by the maximal entropy value to compute the relative visual entropy. The maximal entropy value referred to the equal probability that a participant would fixate one AOI or would shift from one AOI to another. Thus, it represents the complete randomness or unpredictability of the gaze path across AOI and it can be computed as $\log_2(N)$, with N the number of AOI available (Shiferaw et al., 2019). In the context of this study, the relative visual entropy was used to evaluate the degree of goal-directedness in the participants' gaze behaviors, with a high score indicating that the fixations were shifting from one hold to another unpredictably and a low score indicating that the fixations from hold to hold had gained in certainty.

All data treatments were computed on MATLAB R2014a software (Version 8.3.0.532, The MathWorks Inc., Natick, MA, USA).

Statistical analysis

Effects of practice and route design on motor activity and gaze behaviors A two-way repeated-measures analysis of variance (ANOVA) was applied to each dependent measure. The two factors were the three test sessions (practice) and the four climbing routes (route design). When necessary, the *p* values were corrected for possible deviation from sphericity using the Greenhouse–Geisser correction when the mean epsilon was lower than 0.75. Otherwise, the Hyun–Feld procedure was used. Planned simple contrast tests were used to assess the practice and transfer effects on all the dependent variables. The pretest and the Control route were used as references for the practice and route design factors, respectively. Thus, depending on the main factor and interaction effects revealed by the ANOVA, a maximum of 11 tests was performed (see Table 1).

The effect size was determined with the partial eta squared (η_p^2) statistics, with $\eta_p^2 = .01$ representing a small effect, $\eta_p^2 = .06$ representing a medium effect, and $\eta_p^2 = .15$ representing a large effect. ANOVA and contrast tests were performed with SPSS software (Version 21, SPSS Inc., IBM, Chicago, IL, USA), with a level of statistical significance $p < .05$.

The relationship between performance and visual entropy The relationship between GIE and the relative visual entropy was examined using repeated measures correlation (rmcorr), with a level of statistical significance $p < .05$. The aim was to assess whether a complex hip trajectory was correlated with an uncertain gaze path and, conversely, whether a smooth hip trajectory was correlated with a more goal-directed gaze path. This statistical method controlled the effects of between-participant variance on the relationship between the two variables of interest (Bakdash & Marusich, 2017). The rmcorr was performed with the rmcorr R package (https://cran.r-project.org/web/packages/rmcorr/) on RStudio (Version 1.1.383, RStudio Inc., Boston, MA, USA) with R programming language (Version 3.5.1., R Development Core Team, Vienna, Austria).

Results

Performance

Geometric index of entropy The 3 (practice) × 4 (route design) repeated-measures ANOVA revealed a significant effect of practice on GIE, $F(1.08, 6.47) = 21.55$, $p = .003$, $\eta_p^2 = .78$, assumption of sphericity with Mauchly test: $\chi^2(2) = 9.65$; $p = .008$ so the Greenhouse–Geisser correction was applied with $\varepsilon = 0.54$. The simple contrast tests (see Table 1) revealed that the hip trajectory was less complex on the posttest ($M = 0.93$, $SE = 0.05$) and retention test ($M = 1.00$, $SE = 0.07$) compared with the pretest ($M = 1.30$, $SE = 0.05$).

The ANOVA confirmed that the route design also affected the complexity of the hip trajectory, $F(3, 18) = 13.88$, $p < .001$, $\eta_p^2 = .70$. According to the contrast tests, hip trajectory was less complex on the Control route ($M = 0.89$, $SE = 0.03$) than on the Distance ($M = 1.12$, $SE = 0.08$), Orientation ($M = 1.12$, $SE = 0.06$), and Shape ($M = 1.18$, $SE = 0.03$) routes.

The ANOVA also revealed an interaction between practice and route design, $F(6, 36) = 7.71$, $p < .001$, $\eta_p^2 = .56$. The contrast tests showed that between pretest and posttest, participants' GIE decreased more on Control ($M = -0.57$, $SE = 0.07$) than on Shape ($M = -0.14$, $SE = 0.07$) and Orientation ($M = -0.28$, $SE = 0.03$), but it did not significantly differ from that on Distance ($M = -0.49$, $SE = 0.06$). Similarly, the improvement in GIE between the pretest and retention tests was higher on Control ($M = -0.46$, $SE = 0.07$) than on Shape ($M = -0.24$, $SE = 0.09$) and Orientation ($M = -0.17$, $SE = 0.11$), but it did not significantly differ from that on Distance ($M = -0.32$, $SE = 0.10$). The values of GIE on each route and in each test session are displayed in Fig. 3.

Table 1 Results of the contrasts tests on all the dependent variables for the factors Practice (Pretest vs. Posttest and Pretest vs. Retention test) and Route design (Control vs. Distance, Control vs. Shape and Control vs. Orientation) and the interaction of these two factors (Practice × Route Design)

	Practice				Route design						Practice × Route Design											
	Pre × Post		Pre × Re		Control × Dist.		Control × Shape		Control × Orient.		Pre–Post × Control–Dist.		Pre–Post × Control–Shape		Pre–Post × Control–Orient.		Pre–Re × Control–Dist.		Pre–Re × Control–Shape		Pre–Re × Control–Orient.	
	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2
Performance and Exploratory movements																						
GIE	85.88***	.94	13.03*	.69	18.88**	.76	132.49***	.96	36.16**	.86	0.82	.12	109.29***	.95	14.73**	.71	3.00	.33	36.42**	.86	19.99**	.77
NB of Expl.	54.00***	.90	67.50***	.92	/		/		/		/		/		/		/		/		/	
	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2
Gaze behaviors																						
NB of Fixations	18.49*	.82	8.86*	.69	52.68**	.93	180.89***	.98	73.11**	.95	/		/		/		/		/		/.	
Mean Dur. Fix.	/		/		/		/		/		/		/		/		/		/		/	
R. Dur. on AOI	/		/		/		/		/		/		/		/		/		/		/	
R. NB AOI	9.72*	.71	7.59	.66	19.23*	.83	59.26**	.94	56.20**	.93	0.24	.06	6.87	.63	1.39	.26	10.67*	.73	30.97**	.89	18.08*	.82
R. Visual Entropy	17.46*	.81	2.70	.40	15.27*	.79	33.55**	.89	33.53**	.90	/		/		/		/		/		/	

Notes. *$p < .05$; **$p < .01$; ***$p < .001$

/: The contrast test was not performed as the effect of the main factor was non-significant

Pre: Pretest; Post: Posttest; Re: Retention Test

Control: control route; Dist.: transfer route with increased distance between handholds; Shape: transfer route with new handhold shape; Orient.: transfer route with new handhold orientation

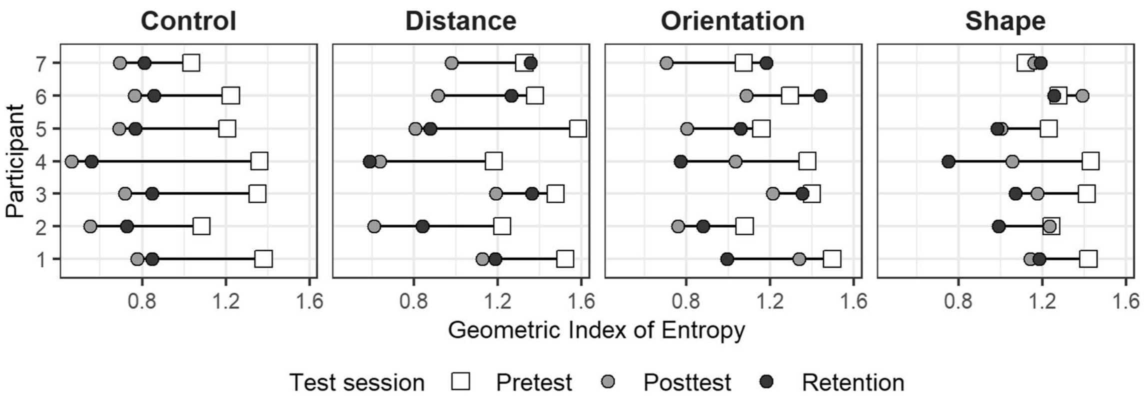

Fig. 3 Participants' individual scores for the geometric index of entropy (GIE). The shape of the points refers to the test session and each frame corresponds to one of the four routes climbed during the test sessions. The lines represent the participants' range of scores for each route. The lower the GIE score, the more fluent the climb of the route

Some interparticipant differences can be highlighted. Participant 7, for example, showed little improvement and even an increase in GIE on the retention test compared with the pretest on the three transfer routes. This participant also showed the least improvement in her GIE on the posttest and retention test compared with the pretest on the Control route. On the other hand, Participants 1, 2, 3, 4, and 5 improved their GIE scores in the posttest and retention test compared with the pretest on the three transfer routes. Moreover, Participants 1 and 4 decreased their GIE on the Orientation route between the posttest and retention test, and similarly, Participants 2, 3, 4 and 5 improved their GIE on the Shape route between the posttest and retention test. Participant 4 also demonstrated the largest improvement in GIE on the posttest and retention test compared with pretest on the Control route.

Number of exploratory hand movements

The 3 (practice) × 4 (route design) repeated-measures ANOVA revealed a significant effect of practice on the number of exploratory movements, $F(2, 12) = 49.38, p < .001, \eta_p^2 = .89$. The simple contrast tests (see Table 1) revealed that the participants performed fewer exploratory movements on the posttest ($M = 1.25, SE = 0.53$) and retention test ($M = 1.04, SE = 0.43$) than on the pretest ($M = 4.25, SE = 0.72$). The ANOVA revealed no significant effect of the route design, $F(1.32, 7.91) = 2.12, p = .186, \eta_p^2 = .26$, Mauchly test: $\chi^2(5) = 12.30; p = .034$, so the Greenhouse–Geisser correction was applied with $\varepsilon = 0.44$, or the Practice × Route design interaction, $F(2.70, 16.2) = 2.43, p = .107, \eta_p^2 = .29$, Mauchly test: $\chi^2(20) = 43.09; p = .008$, so the Greenhouse–Geisser correction was applied with $\varepsilon = 0.45$. The number of exploratory movements performed by the participants on the route handholds is presented in Fig. 4.

Figure 4 showed that Participant 1 performed more exploratory hand movements than the other participants in the three test sessions (at least one on all routes and in all tests). More specifically, this difference between Participant 1 and the others was greatest on the Distance route. Participant 1 also always performed an exploratory movement on handhold 10 of the Control and Distance routes. Conversely, Participants 4 and 5 were the only participants who did not use exploratory hand movements in the retention test on the four routes. Also, in the pretest, Handholds 9, 10, and 11 of the Control and Distance routes appeared to invite the participants to perform more exploratory movements than the other handholds of the same routes.

Gaze behaviors

Tracking ratios Due to poor tracking ratios, the gaze behaviors of two participants were not used in the statistical analysis. We therefore analyzed the gaze behavior of five participants. The tracking ratios for these five ($M = 85.5\%, SE = 2.06\%$) were not significantly impacted by practice, $F(1.05, 4.22) = 0.15, p = .730, \eta_p^2 = .04$, Mauchly test $\chi^2(2) = 6.80, p = .033$, so the Greenhouse–Geisser correction was applied with $\varepsilon = 0.53$, route design, $F(3, 12) = 2.10, \eta_p^2 = .34, p = .154$, or the interaction of the two factors, $F(6, 24) = 1.36, p = .271, \eta_p^2 = .25$, according to the repeated-measures ANOVA.

Number of fixations The 3 (practice) × 4 (route design) repeated-measures ANOVA revealed a significant effect of practice on the number of fixations, $F(2, 8) = 11.16, p = .005, \eta_p^2 = .74$. The simple contrast tests (see Table 1) revealed that the number of fixations was lower on the posttest ($M = 85.30, SE = 4.53$) and retention test ($M = 91.60, SE = 7.04$) than on the pretest ($M = 147.83, SE = 14.06$).

The ANOVA revealed that the route design also affected the number of fixations, $F(3, 12) = 34.66, p < .001, \eta_p^2 = .90$. According to the contrast tests, the number of fixations was lower on Control ($M = 74.83, SE = 4.95$) than on Distance ($M = 111.47, SE = 2.16$), Shape ($M = 129.07, SE = 5.27$), and Orientation ($M = 117.60, SE = 8.02$).

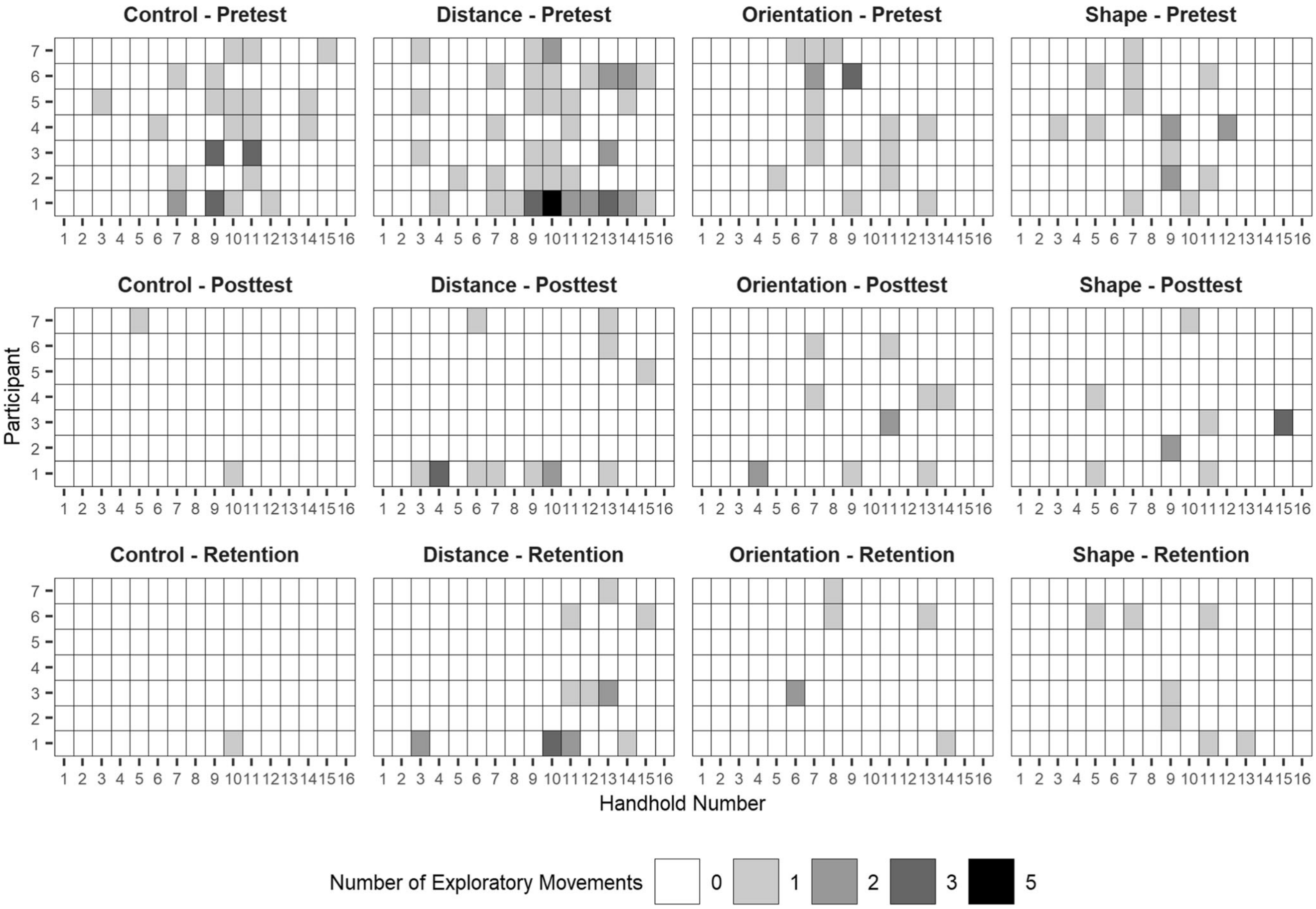

Fig. 4 The heatmaps represent the participants' number of exploratory movements performed on the routes' handholds. On each heatmap, lines correspond to participants and columns to handholds, and the darker the filling, the more the number of exploratory movements on the handholds. Each heatmap corresponds to the ascent of one route in one test session, and they are organized to have one route per column and one test session per line

The ANOVA revealed no significant effect of the Test × Route interaction, $F(6, 24) = 1.18$, $p = .351$, $\eta_p^2 = .23$. Individuals' results are displayed in Fig. 5a.

Mean duration of fixations Practice, $F(1.05, 4.20) = 4.79$, $p = .090$, $\eta_p^2 = .55$, Mauchly test $\chi^2(2) = 7.04$, $p = .030$, so the Greenhouse–Geisser correction was applied with $\varepsilon = 0.53$, route design, $F(3, 12) = 0.64$, $p = .607$, $\eta_p^2 = .14$, and the interaction of the two factors, $F(6, 24) = 0.93$, $p = .491$, $\eta_p^2 = .19$, had no significant effect on the participants' mean duration of fixations ($M = 252.12$ms, $SE = 8.15$ms), according to the ANOVA. Individuals' results are displayed in Fig. 5b.

Relative number of AOI fixated The 3 (test sessions) × 4 (routes) repeated-measures ANOVA revealed a significant effect of practice on the number of fixated AOI, $F(2, 8) = 6.95$, $p = .018$, $\eta_p^2 = .64$. The simple contrast tests (see Table 1) revealed that fewer AOI were fixated on the posttest ($M = 0.78$, $SE = 0.03$) than the pretest ($M = 0.89$, $SE = 0.01$), but the difference with the retention test did not significantly differ ($M = 0.78$, $SE = 0.04$).

The ANOVA confirmed that the route design also affected the number of fixated AOI, $F(3, 12) = 20.33$, $p < .001$, $\eta_p^2 = .84$. According to the contrast tests, the number of visited AOI was lower on Control ($M = 0.76$, $SE = 0.02$) than on Distance ($M = 0.82$, $SE = 0.03$), Shape ($M = 0.85$, $SE = 0.01$), and Orientation ($M = 0.84$, $SE = 0.02$).

The ANOVA also revealed a Practice × Route Design interaction, $F(6, 24) = 3.10$, $p = .022$, $\eta_p^2 = .44$. The contrast tests showed that between pretest and posttest, the number of fixated AOI did not significantly differ between Control ($M = -0.18$, $SE = 0.05$), Distance ($M = -0.14$, $SE = 0.05$), Shape ($M = -0.04$, $SE = 0.03$), and Orientation ($M = -0.09$, $SE = 0.06$). Conversely, between the pretest and retention test, the number of fixated AOI decreased significantly more on Control ($M = -0.21$, $SE = 0.04$) than on Distance ($M = -0.07$, $SE = 0.04$), Shape ($M = -0.09$, $SE = 0.05$), and Orientation ($M = -0.08$, $SE = 0.05$). Individuals' results are displayed in Fig. 5c.

Relative duration of fixations on AOI Practice, $F(2, 8) = 0.93$, $p = .433$, $\eta_p^2 = .19$, route design, $F(3, 12) = 2.14$, $p = .149$, $\eta_p^2 = .348$, and the interaction of the two factors, $F(6, 24) = 0.37$,

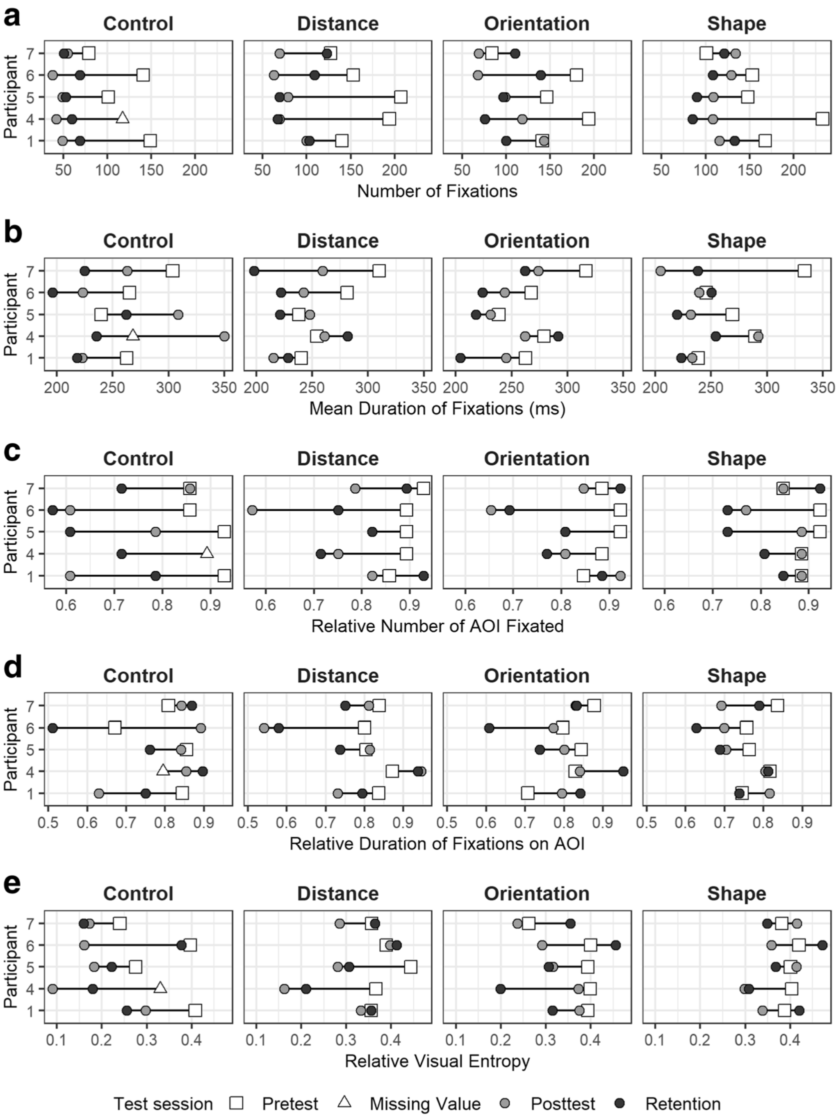

Fig. 5 Participants' individual values for the five dependent variables measured to assess gaze behaviors: (**a**) the number of fixations, (**b**) the mean duration of the fixations, (**c**) the relative number of AOI fixated, (**d**) the relative duration of fixations spent on AOI, and (**e**) the relative visual entropy. The shape of the points refers to the test session. The values for Participant 4 on the pretest for the Control route are replaced by the mean of the series

$p = .892$, $\eta_p^2 = .08$, had no significant effect on the participants' relative duration of fixations on AOI ($M = 0.78$, $SE = 0.03$), according to the ANOVA. Individuals' results are displayed in Fig. 5d.

Relative visual entropy The 3 (practice) × 4 (route design) repeated-measures ANOVA revealed a significant effect of practice on the relative visual entropy, $F(2, 8) = 5.17$, $p = .036$, $\eta_p^2 = .56$. The simple contrast tests (see Table 1) revealed that the gaze path was more goal-directed on posttest ($M = 0.29$, $SE = 0.02$), compared with pretest ($M = 0.37$, $SE = 0.02$), but did not differ significantly on the retention test ($M = 0.32$, $SE = 0.03$).

The ANOVA revealed that the route design also affected the relative visual entropy, $F(3, 12) = 18.09$, $p < .001$, $\eta_p^2 = .82$. According to the contrast tests, the gaze path was more goal-directed on Control ($M = 0.25$, $SE = 0.03$) than on Distance ($M = 0.33$, $SE = 0.03$), Shape ($M = 0.38$, $SE = 0.01$), and Orientation ($M = 0.34$, $SE = 0.02$). The ANOVA did not reveal any significant effect of the Test × Route interaction, $F(6, 24) = 1.38$, $p = .262$, $\eta_p^2 = .26$. Individuals' results are displayed in Fig. 5e.

Relationship between performance and visual entropy

A repeated-measures correlation was computed to assess the relationship between GIE and the relative visual entropy on the four routes (see Fig. 6). The results showed a positive correlation between the two variables on Control, $r_{rm}(9) =$

.83; 95% CI [0.38, 0.96]; $p = .001$, Distance, $r_{rm}(9) = .84$; 95% CI [.41, .98]; $p = .001$, and Orientation, $r_{rm}(9) = .84$; 95% CI [.39, .96]; $p = .001$. Thus, the more complex the participants' hip trajectory was on these routes, the more uncertain their gaze path was across AOI. Conversely, the smoother their hip trajectory was, the more goal-directed their gaze path was. However, this relation was not significant on Shape, $r_{rm}(9) = .38$; 95% CI [−.38, .83]; $p = .254$ (Fig. 6).

Discussion

The first aim of this study was to investigate the modifications of learners' exploratory activity during the acquisition of a perceptual-motor skill. The second aim was to determine to what extent the acquired perceptual-motor skill and the learners' exploratory activity were transferred to environments presenting novel properties. The results validated our hypothesis that the participants' exploratory activity would be more efficient with learning, as shown by (i) the decrease in the number of exploratory movements and fixations and (ii) the gain in goal-directedness of the gaze behavior on the learning route. Regarding the transfer of the route-finding skill, the results suggest that the participants transfer their skill to the route with an increased distance between handholds but not to the other two routes. Also, there were fewer exploratory movements following practice on the three transfer routes, which indicates that these learners relied more on exploration from a distance with learning. However, the number of fixations on the transfer routes was higher than on the learning route and a positive correlation between the entropy of the hip trajectory and the gaze path was observed on all routes except the route with a different handhold shape.

Less exploratory hand movements with learning

The results showed that the number of exploratory movements decreased with learning and that Participants 4 and 5 were not even using these hand movements on the retention test for the four routes. This decrement in exploratory behaviors is in

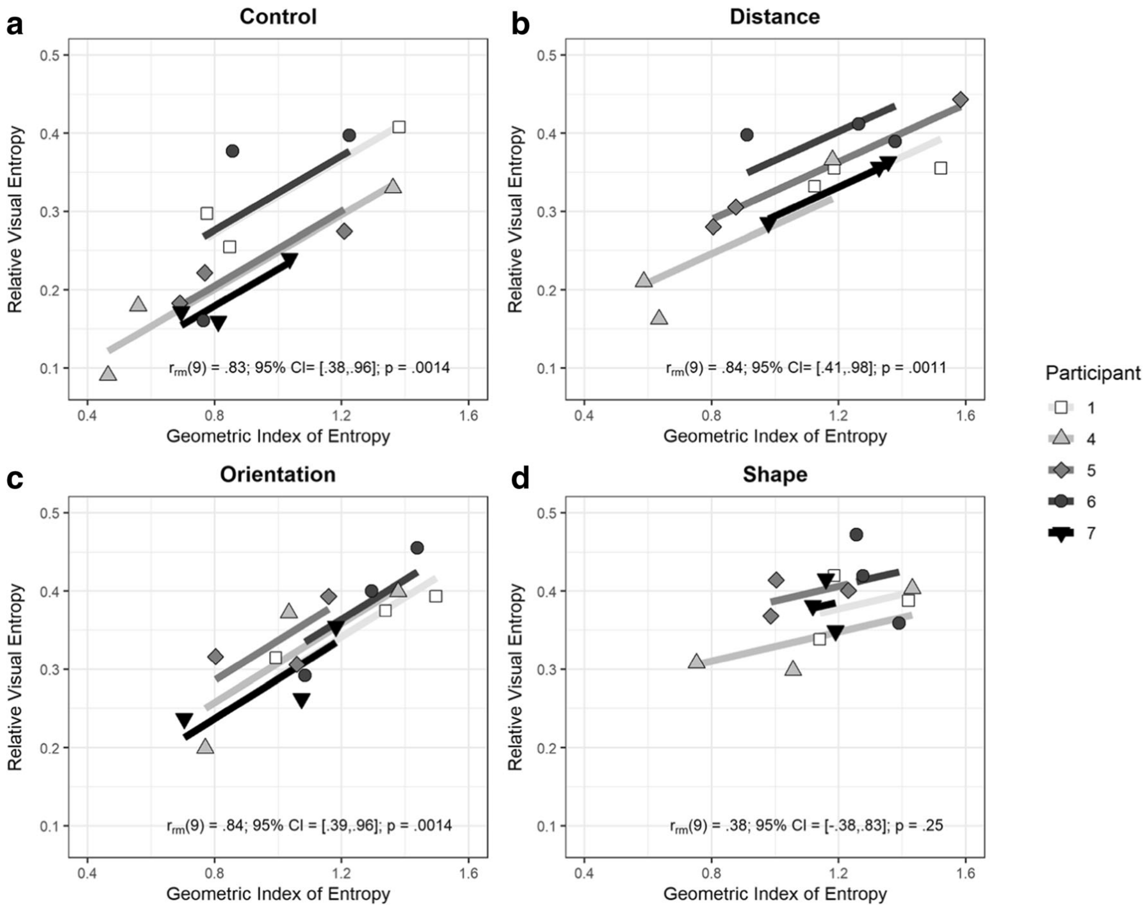

Fig. 6 Relationship between the geometric index of entropy and relative visual entropy. This figure displays the results of the repeated measures correlations (r_{rm}) with the boundaries of the 95% confidence interval (95% CI) and the *p* value. Each panel corresponds to one of the four routes performed during the test sessions: Panel **a** refers the control route; **b** refers the route with and increased distance between handholds; **c** refers to the route with new handhold orientation; and **d** refers to the route with new a handhold shape. The points represent the participants' trials ($N = 60$), and the color identifies the participants. The lines represent the repeated-measures correlation fit for each participant

accordance with the literature. In climbing studies specifically, the number of exploratory movements either became lower in the learning protocols (Orth et al., 2018b; Seifert et al., 2018) or increased in conditions of anxiety (Nieuwenhuys et al., 2008; Pijpers et al., 2005; Pijpers et al., 2006). Exploratory hand movements were also studied by confronting participants with tasks involving surprising ground surfaces (Joh & Adolph, 2006). This study suggested that exploratory movements were used to reveal haptic information about, for example, ground texture or ground density to avoid falling. Similarly, participants in the present study may have used exploratory hand movements initially to reveal information about handhold texture or saliences (i.e., bumps and hollows). However, no significant differences were observed between the number of exploratory movements on the Control route and the transfer routes following the learning sessions, which suggests that the information revealed by haptic exploration on the control route could be transferred to the transfer routes. Thus, haptic exploration had a prospective role, but the importance of this role seemed to decrease with experience. According to Kretch and Adolph's (2017) hypothesis of the ramping-up organization of exploratory actions, touching is one of the most engaging modes of exploration, as it brings the individual into direct contact with an unknown surface. In the case of a climbing task, touching can inform on hold texture, shape, size, orientation, etc., in order to aid decisions on grasping and to apply friction forces. However, touching with a hand implies that the arm is no longer a support. Moreover, the task-goal (i.e., to climb the route as fluently as possible) may have prevented the participants from engaging in haptic exploration as it implied stops in the ascent. Thus, it is fair to assume that the decrease in the number of exploratory movements with practice was linked to the following: (i) over the course of practice, the climbers came to need the information revealed through these exploratory movements less and (ii) the exploratory movements were threatening to high performance or safety. Thus, in line with Kretch and Adolph's (2017) ramping-up hypothesis, exploration with learning may have been dominantly performed from a distance by the visual system.

Nevertheless, exploratory hand movements were still used following the leaning sessions and may have had other functions. Figure 4 shows that these movements were unequally used by the participants. Participant 1 in particular used these movements remarkably more than any other participant in all the test sessions. These individual differences suggest that the participants may not have performed exploratory hand movements with the same purpose. Moreover, Fig. 4 suggests that the exploratory movements were used mainly on specific handholds (e.g., Handholds 9, 10, and 11 on the Control and Distance routes) and that, even though the handholds were the same on the two routes, there seemed to be a tendency for fewer exploratory movements on the Control route than on the route with an increased distance between handholds, notably for Participant 1. Thus, this mode of exploration may have been used by the participants (i) to better perceive whether the handhold was within reaching distance, (ii) to adjust their body position in order to prepare the next movement, or (iii) to try/adjust different grasping patterns in order to ensure the following movement. Exploratory movements may have been used at the beginning of the learning sessions to reveal information about handhold texture, but other functional roles would explain why this mode of exploration was still used after the sessions. However, these other functional roles need further and more specific investigations to be confirmed.

Less gaze activity with learning

The results showed that after the learning sessions, the participants performed fewer fixations while they were climbing, but the duration of these fixations and the percentage of their viewing time spent fixating AOI (i.e., holds of the route) were not affected. These findings indicate that less gaze activity is needed with practice. Similar results were found in a climbing task with more experienced climbers: They reduced the number of fixations during ascents, but the number of fixations per second (i.e., search rate) did not change with practice (Button et al., 2018). Thus, in accordance with the literature, the quantity of gaze activity seemed to decrease with learning as fewer fixations were performed to climb the routes.

Other variables may be useful for describing the state of visual exploration and the changes in the function of vision with learning. In their systematic review, Kredel et al. (2017) showed that the variables usually measured to investigate gaze behavior in performance contexts reveal (i) the source of information that performers rely on and (ii) the quantity of information taken from these sources. As illustrated by our results, these variables only reveal the changes in the quantity of gaze activity but not the qualitative changes induced by learning. Thus, in what follows, we discuss the use of the visual entropy measure to assess the learning-induced changes in the gaze path during the ascents.

Reorganized gaze behavior with learning

As the relative duration spent on AOI did not change between pretest and posttest, it did not seem that the learners were searching for the holds on the wall and that as they learned they knew where to find the relevant information. Thus, it seems that with learning, the climbers did not merely change the quantity and sources of information to climb fluently. Instead, the results on visual entropy showed that the gaze path reorganized as it appeared to have become more goal-directed on the posttest compared with the pretest: the learners used vision first to look for handhold affordances by fixating them in an uncertain order, and then to guide their climbing actions by fixating the handholds in a more structured order. The results also showed that the number of fixated AOI (i.e., holds on the wall) decreased with learning, and if we refer to the formula used to compute the visual entropy (see Methods: Dependent Measures), this can affect visual entropy. Thus, the decrease in visual entropy can be attributed to (i) a more goal-directed gaze transition between climbing holds and (ii) a decrease in the number of fixated holds.

Although the quantity of gaze activity was lower on the retention test than on the pretest, this long-term effect was not observed for the reorganization of gaze behavior, even though the number of fixated holds was still lower during the retention test on the Control route than on the transfer routes. Here, again, it seems that it was not sufficient to decrease the quantity of gaze activity to climb fluently, but that the learners also had to obtain information for affordances from the visual system to guide their actions. Indeed, the results on the retention test suggest that the learners were still not fixating some holds of the route (as in the posttest) but were shifting from one hold to another in a more uncertain way. Thus, it seems that the learners had more difficulty guiding their actions on the climbing route than they did on the posttest.

The repeated-measures correlations calculated between GIE and visual entropy tended to confirm this insight: the more visual entropy decreased, the more the visual system seemed to be used to guide locomotion on the route. This relation between the two variables appeared to hold on all routes except the one with the new handhold shape. These results suggest that the new handholds of the Shape route disrupted the information-movement couplings developed on the Control route which prevented participants to transfer their exploratory activity and their route-finding skill to this new environment (see the following section for further discussion).

The reorganization of the gaze behavior can be discussed in the light of the recent hypothesis that exploratory activity differs according to the aim of exploration: exploration for orientation or exploration for action specification (van Andel et al., 2019). According to this hypothesis, exploration for orientation refers to the discovery of the different affordances that can be realized, whereas exploration for action specification refers to the selection of one affordance and the specification of its requirements in terms of movement control. The results on the reorganization in the participants' gaze behaviors on the posttests and the positive correlation between visual entropy and climbing fluency, seem to support this hypothesis on the learning timescale. Indeed, they suggest that exploration may have changed from a dominant aim to discover the affordances of the routes in the pretest, to exploration dominantly aimed at specifying the climbing movements in the posttest. However, further investigation is necessary to validate this assumption.

Limited transfer of route-finding skill to the new environments

The results validated the effect of practice on the learners' route-finding skill, which is a prerequisite to then assure the transfer of learning. GIE decreased significantly on the post-test and retention test in comparison to the pretest. This result indicates that the learners adopted a less complex and smoother hip trajectory to reach the top of the climbing route, thereby demonstrating more fluency in the chaining of their climbing movements (Orth et al., 2018a) and a higher degree of coherence in their perception-action coupling (Cordier et al., 1994).

The transfer of route-finding skill to the climbing routes with local changes appeared limited. Although five of the seven participants showed improved climbing fluency on the three transfer routes in the posttest and retention test compared with the pretest, the results suggest that, as expected, the participants could effectively adapt their climbing actions when the new properties invited low-order behavioral changes (Distance route), but that they had more difficulties to adapt their climbing actions when the new properties induced high-order behavioral changes (Orientation route). Also, the results suggest that the change in handholds shape prevented transfer, although the handholds could be used similarly to the original handholds (Shape route).

The lack of transfer to the Orientation route can be discussed at the light of the literature about transfer of calibration. In this literature, two opposite views exist. On one hand, a series of experiments by Rieser et al. (1995) proposed that the calibration of one coordination transfers to other coordinations that share the same function (e.g., calibration of forward walking transferred to side stepping). Similar findings were obtained in a more recent experiment that showed that calibration transfers from walking to crawling (Withagen & Michaels, 2002). On the other hand, results in developmental studies showing that calibration was specific to the postural milestone, as children who were discovering new postures (e.g., learning to crawl) did not transfer their calibration from earlier postures (e.g., sitting to crawling), but had to discover the action boundaries enabled by the new posture (Adolph et al., 2008; Kretch & Adolph, 2013). Our results seem to fit the latter assumption that calibration is posture specific. Indeed, the high-order behavioral changes due to the change in handhold orientation may have disrupted the learners' chain of climbing actions by leading them into body postures that they had not previously experienced and that changed the actions they could perform with the following handholds. As already observed, adapting to change in hold orientation requires lengthy practice as it forces the body to rotate from side to side like a pendulum and this body rolling must be controlled, whereas beginners naturally climb facing the wall (Seifert et al., 2015). To produce a positive transfer to the Orientation route, it is possible that the new body postures would have also needed to already be in the learners' motor repertoire prior to the transfer test.

Transfer of the route-finding skill was also negative on the Shape route. The new handholds were chosen to enable the same grasping pattern as the original handholds, but this pattern was hidden from the learners so that they would have to find the functional properties on the new handholds that were similar to those of the originals. Previous studies have shown that with expertise climbers develop a functional perception of the handholds as they perceive them in terms of the affordances that they allow rather than their structural properties (e.g., their dimensions, size, color; Bläsing et al., 2014; Boschker et al., 2002). According to our results, the learners did not transfer their functional perception from the Control route to the Shape route, so they may have used unreliable information to perceive affordances on the Control route, preventing a possible transfer of attunement (Smeeton et al., 2013). Thus, the learners may have built their functional perception on the Control route on information that was too specific to the original handholds and that could not be retrieved with the new handholds of the Shape route, which conforms with the fundamental idea that affordances perception builds on highly specific individual-environment relationship (Gibson & Gibson, 1955). Interestingly, four participants improved their climbing fluency on this route between the posttest and retention test. This unusual result suggests that they may have benefited from the posttest trial to better perceive the affordances of the new handholds. This would also be congruent with the original proposition of Gibson and Gibson (1955) that perception of affordances builds on specific individual-environment relationships that develops with practice.

It should be also stressed that the protocol did not have the same effect on all the participants. Some interparticipant differences were observed, notably for the progression of Participants 4 and 7 on the routes. Participant 7 showed the least improvement in climbing fluency, this fluency being even worse on the retention test than the pretest for the three transfer routes. In contrast, Participant 4 showed the greatest improvement while learning on the Control route, but also demonstrated considerable improvement on the three transfer routes, with a posttest result that improved even more on the retention test. Participant 4 may have greatly benefited from the learning sessions by developing skilled exploratory activity that gave him the ability to rapidly adapt to new features on the climbing routes (Adolph, 2008; Gibson, 1966).

Limitations and perspectives

This study is original because it investigates gaze behaviors in a task representative of climbers' real activity (for a review of eye-tracking studies in sports, see Kredel et al., 2017). We proposed to use the relative visual entropy to assess the degree of goal-directedness from the spatial pattern of the gaze movements during the participants' ascents. This measure may be useful for informing qualitative changes in the spatial organization of the performers' gaze path in a rich and complex environment such as in this climbing task. However, the main limitation was the low number of participants whose gaze behavior could be used; this is a problem often encountered in the eye-tracking literature (Dicks et al., 2010; McGuckian et al., 2018; van Dijk & Bongers, 2014). Moreover, given the high variability in the participants' gaze behaviors (see Fig. 5), care is needed in drawing conclusions, and future research could focus more on the different strategies in gaze behaviors mobilized by performers (Dicks et al., 2017).

Also, the method used to assess the number and location of hand exploratory movements showed some limitations. Although numerous studies have used this method in climbing tasks, it is debatable whether a hand movement initially used with a primary informational purpose can reveal an appropriate fit between the climber and the handholds and enable the climber to turn exploratory movements into performatory ones. Thus, even though this method provides some insight into participants' attunement to handholds affordances, more precise methods could be developed to investigate climber–handholds interactions in order to achieve a finer-grained understanding of how climbers reveal and exploit information about handholds affordances. One example might be an analysis of their eye–hand coordination when they use or touch the handholds.

Conclusion

To summarize, this study helps to show how exploratory activity changes with the practice of a climbing task and to what extent this exploratory activity and the route-finding skill of learners could transfer to climbing routes with new handholds properties. Exploratory hand movements did not appear to be used solely to gather information as it seemed that some participants used them with additional functional purposes to climb the routes. The gaze activity appeared to decrease (fewer fixations during ascents) and reorganize with practice, which suggests that visual exploration was initially used by the learners to search the environment and then to guide their actions. However, although there was still less gaze activity on the retention test, its level of goal-directedness decreased; thus, the participants may have needed to search anew for the relevant information to guide their climbing movements. The individual performances in the tests indicate that some participants benefited more than others from the learning sessions to develop skilled exploratory activity. Performances at the group level suggest that the participants were able to transfer their route-finding skill to a new climbing route if (i) they had mastered the actions enabled by the new properties of the environment and (ii) they were attuned to the functional properties of the new environment.

Open practices statement The datasets generated for this study are available on request to the corresponding author. The experiment was not preregistered.

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