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Skill transfer, affordances and dexterity in different climbing environments

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ABSTRACT

This study explored how skills in one region of a perceptual-motor landscape of performance, created in part by previous experience in rock climbing, can shape those that emerge in another region (ice climbing). Ten novices in rock climbing and five intermediate rock climbers were observed climbing an icefall. Locations of right and left ice tools and crampons were videotaped from a frontal camera. Inter-individual variability of upper and lower limb couplings and types of action regarding icefall properties were assessed by cluster hierarchical analysis, distinguishing three clusters. Pelvis vertical displacement, duration and number of pelvis pauses were also analyzed. Experienced rock climbers were grouped in the same cluster and showed the highest range and variability of limb angular locations and coordination patterns, the highest vertical displacement and the shortest pelvis plateaux durations. Non-fluent climbers (clusters 2 and 3) showed low range and variability of limb angular locations and coordination patterns. In particular, climbers of cluster 3 exhibited the lowest vertical displacement, the longest plateaux durations and the greatest ratio between tool swinging and definitive anchorage. Our results exemplified the positive influence of skills in rock climbing on ice climbing performance, facilitated by the detection of affordances from environmental properties.
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1. Introduction

According to ideas in ecological dynamics, skilled individuals are seen as capable of exploiting available information about environmental and task-related constraints in order to re-organize the multitude of motor system degrees of freedom during performance of multi-articular actions (Davids, Button, & Bennett, 2008). The acquisition of skilled behavior is influenced by the gap that may exist between a stable pre-existing movement pattern repertoire in a specific performance environment and a 'to-be-used' pattern in another region of the perceptual-motor landscape of performance. An important issue in movement science concerns the ability to adapt one's intrinsic system dynamics (existing coordination tendencies) to the specific constraints of a new task. From this viewpoint, harnessing previous experience is defined by the amount of adaptability between each individual's intrinsic dynamics and the dynamics of a task in a different performance environment with new ecological constraints that need to be satisfied (Warren, 2006). Adaptability refers to a subtle, functional blend between stability (i.e., persistent behaviors) and flexibility (i.e., variable behaviors) in achieving task goals (Davids, Bennett, & Newell, 2006; Li, Haddad, & Hamill, 2005; Warren, 2006). Adaptability was termed 'dexterity' by Bernstein (1967), and is essential to skilled performance of complex multi-articular actions. In skilled individuals, stability is characterized by the consistent achievement of performance outcomes over time, resistant to perturbations and reproducible in the sense that a relatively similar movement pattern may recur under different task and environmental constraints. Stable behaviors do not signify the existence of stereotyped and rigid movement patterns to achieve consistent performance outcomes. Rather, dexterity underpins functional movement patterns, displaying regularities and similarities within their structural components, with an individual not locked into a rigid, repetitive performance solution. It is, thus, important to understand which components of multi-articular actions remain stable and reproducible in dynamic performance environments with different ecological constraints on action, such as team sports (e.g., football and futsal), cycling (e.g., road racing and mountain biking), paddle sports (white water and ocean kayaking) and outdoor pursuits (e.g., indoor wall, rock and ice climbing). Here we sought insight into the capacity of skilled individuals to harness previous experience in rock climbing to satisfy the task constraints of climbing in a distinct performance environment: scaling icefalls.

Regarding the ecological dynamics of skill acquisition, investigation of how individuals acquire new forms of behavior against a background of a pre-existing movement pattern repertoire has historically been an aspiration in motor learning research, typically using rhythmical movement models (e.g., Buchanan, 2004; Kelso & Zanone, 2002; Temprado & Swinnen, 2005; Wang & Sainburg, 2004; Zanone & Kelso, 1997). However, few investigations have attempted to explore how skill acquisition occurs when performing complex multi-articular actions in dynamic performance environments (such as climbing on various surfaces). In our study, this issue was exemplified in an investigation of which aspects of previous experience are reproducible, stable and transferred from rock to ice climbing. Specifically, the issue was examined by observing how rock climbers used their previous experiences in climbing a frozen waterfall surface, known as ice climbing. The issue of skill transfer from rock to ice climbing can provide much-needed theoretical, practical and pedagogical insights.

Three main points emphasized our expectations of a positive transfer of climbing experience between the specific task constraints of rock and ice climbing: (i) the coupling of perception and action in unpredictable environments, (ii) alternation between maintaining body equilibrium and climbing quickly up a vertical surface, and (iii) the use of quadrupedal locomotion in using the extremities of each limb.

(i) In dynamic and natural performance contexts such as rock and ice climbing, task expertise relates to the coupling of an individual's actions with affordances (i.e., action possibilities offered by properties of the environment; Gibson, 1979) in the performance environment. Considering affordances as opportunities for action in the context of rock and ice climbing suggests that the coordination dynamics of action would emerge from a mutual coupling of a climber's

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perceptions and intentions with the specific properties of a climbing surface, such as a rock cliff (i.e., shape, steepness, type of rock) or an icefall (i.e., shape, steepness, temperature, ice thickness and density of a frozen water fall). This mutual coupling is assumed because a particular emergent movement pattern and the conditions of the rock or ice cannot be predicted and planned from the ground.

(ii) Interacting task and environmental constraints characterize both rock and ice climbing performance contexts; in particular, the performer has to maintain body equilibrium on a climbing surface (Bourdin, Teasdale, Nougier, Bard, & Fleury, 1999) and needs to integrate upper and lower limb movements according to structural and functional aspects of the performance environments to ascend a surface (Boschker, Bakker, & Michaels, 2002; Seifert, Wattebled, L'Hermette, & Hérault, 2011b).

(iii) In contrast to adult human pedestrian locomotion, climbing an overhanging surface corresponds to quadrupedal locomotion in the vertical plane involving a minimal support of one limb (or more) in order to counteract gravitational forces and not fall down (Sibella, Frosio, Schena, & Borghese, 2007). The support for a limb on a climbing surface corresponds to an articulation with small points of contact on the rock cliff (Phillips, Sassaman, & Smoliga, 2012) or ice fall, using the extremities of fingers and feet, or tools (such as ice tools and crampons). Because of these specific task constraints the control of actions with respect to gravitational forces is much more challenging than during human pedestrian locomotion in the horizontal plane.

Nevertheless, the task constraints of ice climbing reveal at least three specificities in comparison to rock climbing which form the basis of affordances for action (Seifert, Wattebled et al., 2011b): (i) The climber-icefall coupling is mediated by tools to interact with surfaces properties, such as ice tools for the hands and crampons for the feet; (ii) The ice fall properties tend to be stochastically distributed throughout its surface; for instance, ambient temperature may modify ice density in certain regions of the ice fall; and (iii), The climbers determine their own climbing path as they can create their own anchorages with their tools and secure their ascent by screwing ice screws in specific locations they want in the ice fall.

The specific question we were interested in is: Are rock climbers, who have already experienced common ecological constraints of climbing, able to transfer their experiences and components of their skills to the distinct performance environment of ice climbing? Or is the mode of individual-environment coupling and the tool use much too specific to permit any transfer of previous experience between the two distinct sets of task constraints? We hypothesized that participants with previous experience in rock climbing would attempt to exhibit adaptive large range of coordination patterns, climbing fluency, affordance detection (i.e., exemplified by the ability to adapt types of action and number of actions to ice properties) in the ice climbing task.

2. Methods

2.1. Participants

Fifteen students in a faculty of sport sciences at a local university volunteered for this study (mean age: 24.5 ± 4.5 yr; mean height: 175.1 ± 8.5 cm; mean weight: 72.1 ± 12.8 kg; $M \pm SD$). This sample was composed of ten novices in rock climbing (climbing ability below 5 on the French Rating Scale of Difficulty; Delignières, Famose, Thépeaut-Mathieu, & Fleurance, 1993; Draper et al., 2011), who had undertaken 10 hours of practice on an artificial climbing wall, and of five intermediate rock climbers, with a climbing ability of 6a (intermediate climbing ability on the French Rating Scale of Difficulty; Draper et al., 2011) and 3 years of experience in rock climbing. However, it is important to note that all the climbers in our sample were inexperienced at ice climbing.

2.2. Protocol

The participants were asked to climb a 30-m icefall by top rope at grade 4, on the French rating scale, which goes from 1 to 7 (Batoux & Seifert, 2007). Grade 4 is a common grade assigned to novice

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skill level and involves alternation of steep sections around 80 to 85° with ramps around 60–70°. For this protocol, the icefall selected for the beginners was in three sections: 15 m at 85°, ramp of 8 m at 70°, then 7 m at 80°. Performance data were collected in two sessions on two separate days during which the air temperature was respectively −8°C and −12°C. All climbers were equipped with the crampons and ice tools and were instructed to climb at their normal preferred pace. The protocol was approved by the local University ethics committee and followed the declaration of Helsinki. Procedures were explained to the climbers, who then gave their written informed consent to participate.

2.3. Data collection

A frontal camera (25 Hz), positioned 15 m behind the climber perpendicular to the icefall, digitally recorded the first 20 m of the climb. According to Seifert, Wattebled et al. (2011b), a calibration frame delimited the recorded space of climbing performance and was composed of one vertical rope with marks every 2 m and two horizontal ropes (at 5 m and at 20 m) with marks every 1 m (total of 20 marks for calibration). Five key points (the pelvis, the head of left and right ice tools and the lowest position of left and right crampons) were digitised using Simi Motion Systems® (2004).

2.4. Data analysis

2.4.1. Performance outcomes and fluency of climbing movement

Since climbing was self-paced in this study, the time of ascent was not considered in assessing performance. The first steep section of the icefall was used to measure the performance outcomes which corresponded to the distance travelled by the pelvis of each participant in the vertical axis during a 5-min period (as the rate of camera was 25 Hz, $n = 7500$). Previous studies have assessed the fluency of climbing movements by a harmonic analysis of the acceleration of the body's centre of mass (Cordier, Dietrich, & Pailhous, 1996), by quantifying the duration of static position as any point throughout the climb where the hips were not in motion (Billat, Palleja, Charlaix, Rizzardo, & Janel, 1995) or by the geometric entropy indices from the displacement of the body's centre of mass (Cordier, France, Pailhous, & Bolon, 1994; Sanchez, Boschker, & Llewellyn, 2010; Sibella et al., 2007). Based on this previous work, we assessed the fluency of climbing movement by recording the average number of plateaux and average plateau duration from the pelvis vertical distance-time curve of each climber. A plateau was considered as a vertical axis pelvis displacement less than 0.15 m for durations longer than 5 s, which was the average duration corresponding to one movement of each limb (right ice tool swinging + left ice tool swinging + right crampon kicking + left crampon kicking). A plateau was detected by an algorithm which provided a moving window on the whole signal: when the difference between the two points delimiting the window was higher than a fixed threshold (in our case, vertical axis pelvis displacement values greater than 0.15 m) a break point was detected in the window. The difference was an Euclidean distance (d) following Eq. (1):

$$d = \sqrt{\sum_{i=1}^{k}(X_i - Y_i)^2} \tag{1}$$

where X and Y are the two points delimiting the window. Moreover, another threshold (in our case, a plateau duration >5 s) was selected in order to avoid doublets in the detection. If two break points were lower than this threshold value, the algorithm ignored the new break point detected.

2.4.2. Inter-limb coordination

After previous work (Seifert, Wattebled et al., 2011b), upper limb coordination patterns were assessed by using the angle between the horizontal plane and the line formed by the position of the heads of the left and right hand ice tools for the 5-minute period (as previously, $n = 7500$). Lower limb coordination patterns corresponded to the angle between the horizontal plane and the line formed by the lowest position of the left and right crampons (Fig. 1). These two signals were smoothed by a Butterworth low-pass filter (cut-off frequency 6.25 Hz) by Matlab 7.7® (1984–2008, The MathWorks,

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Inc.). When the angle was 0 ± 22.5°, the two limbs were horizontal, meaning that they were simultaneously flexed or simultaneously extended, corresponding to an in-phase mode of coordination. When the angle was +or− 90 ± 22.5°, one limb was vertically located above the other limb, meaning that one was extended, while the other was flexed, corresponding to an anti-phase mode of coordination. Between these values, limb location was considered as oblique and coordination was considered in an intermediate mode.

The angle between the horizontal line and the left and right limbs was positive when the right limb was above the left limb and negative when the right limb was below the left limb (Fig. 2).

The phase angles of the upper and lower limbs were obtained by Hilbert transform (Matlab 7.7.0.471® (The MathWorks Inc., U.S., R2008b), usually calculated for non-periodic signals (Balasubramaniam & Turvey, 2004; Post, Daffertshofer, & Beek, 2000; van Emmerik, Rosenstein, McDermott, & Hamill, 2004):

$$\text{Phase} = \arctan s(t)/H(t) \tag{2}$$

with s(t) as the real part and $H(t)$ the imaginary part of the signal. After Rosenblum and Kurths (1998), $H(t)$ was obtained in Eq. (3):

$$H(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}\,d\tau \tag{3}$$

where $x(t)$ is a given time series. The relative phase $\phi(t)$ between upper and lower limbs given in degrees for two time series upper limbs *upper*(t) and lower limbs *lower*(t) was obtained in Eq. (4):

$$\phi(t) = \arctan[H_{upper}(t) * s_{lower}(t) - s_{upper}(t) * H_{lower}(t)]/[s_{upper}(t) * s_{lower}(t) - H_{upper}(t) * H_{lower}(t)] \tag{4}$$

Fig. 1. Angle between the horizontal line and the line formed by the position of the left and right tools.

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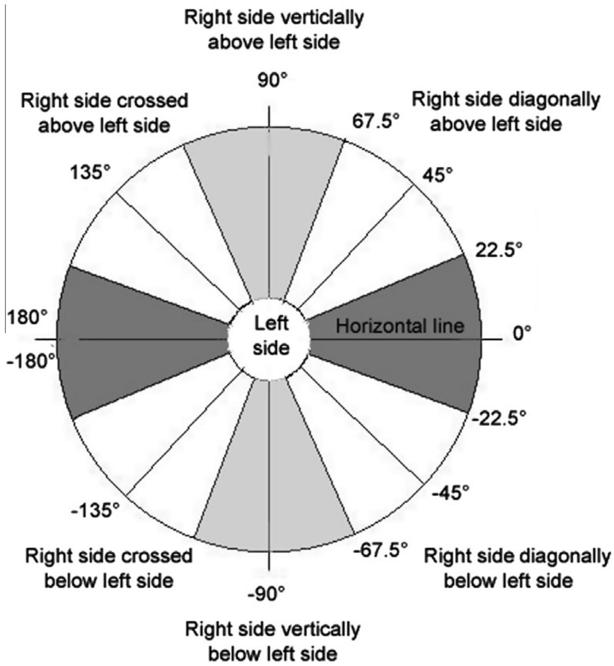

Fig. 2. Modes of limb coordination as regards the value of the angle between the horizontal line and the line formed by the position of the left and right tools.

An in-phase mode of coordination was assumed to occur for $-22.5^\circ < \phi(t) < 22.5^\circ$ (Fig. 3) and meant that upper and lower limbs showed similar angular locations. An anti-phase mode of coordination was taken to be between $-180^\circ < \phi(t) < -157.5^\circ$ and $157.5^\circ < \phi(t) < 180^\circ$ (Fig. 3) and meant that upper and lower limbs showed opposite angular locations (e.g., -90° for the upper limbs coordination and 90° for the upper limbs coordination). Between these values, coordination was considered to be in an intermediate mode and meant that upper and lower limbs showed a gap >22.5° in their angular locations (e.g., 90° for the upper limbs coordination and 0° for the upper limbs coordination). Finally, mean and standard deviation data of $\phi(t)$ were calculated throughout the 5-minute period for each individual.

2.4.3. Affordances detection

Assuming that affordances corresponded to invitations for action offered by the environment, two types of indicators can explain how climbers detect affordances, i.e., exploit environment properties to act: (i) the types of action, and (ii) the number of actions used to anchor the tools. Different types of action could be realised (i.e., swinging, kicking or hooking) depending on the icefall shape: when the ice is dense without any holes, climbers usually swing their ice tools and kick their crampons. Conversely, when the ice is hollow, climbers hook holes with their ice tools and crampons. Thus, the capability of affordance detection could be assessed by the ability of each climber to vary the types of action used to engage with the icefall. Based on this logic, two ratios were calculated: (i) the ratio between ice tool swinging and holes hooking, (ii) the ratio between crampon kicking and holes hooking. The number of actions to anchor the tools could also reveal the capability of affordances detection: when the ice is soft or ventilated, climbers can anchor their ice tools and crampons in one shot. Conversely, when ice is dense and thick, climbers repeat numerous ice tools swinging and crampons kicking to attain a safe anchorage. Based on these ideas, two ratios were calculated: (i) the ratio between repetitive ice tool swinging and definitive anchorage, and (ii) the ratio between repetitive crampon kicking and definitive anchorage. A low ratio would be a mark of high performance. A similar indicator, known as the 'three-holds-rule', is already used in rock climbing to detect skill in climbing quickly up a vertical surface. Sibella et al. (2007) showed that skilled climbers move fast by using fewer than three holds, meaning that climbers touched fewer than three surface holds before grasping the functional one. Therefore, the holds touched/grasped ratio could give an indication of the capability for affordance detection in rock climbing.

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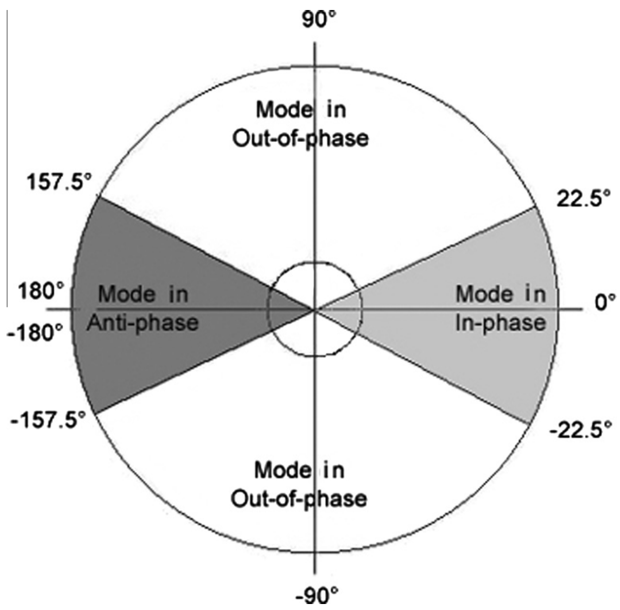

Fig. 3. Upper-lower limb coordination modes: In-phase mode of coordination was assumed to occur for $-22.5° < \phi(t) < 22.5°$; anti-phase mode of coordination was taken to be between $-180° < \phi(t) < -157.5°$ and $157.5° < \phi(t) < 180°$; between these values, coordination was considered to be in an intermediate.

2.5. Statistical analysis of the data

Inter-individual variability of movement patterns was investigated by a cluster hierarchical analysis, as advised by Ball and Best (2007) and Rein, Button, Davids, and Summers (2010), in order to classify different participant profiles and examine whether transfer of previous experience induced rock climbers to be categorized in the same cluster or not. Cluster analysis, by unsupervised machine learning (Duda, Hart, & Stork, 2001), is a relevant technique to detect patterns within high-dimensional datasets, in our case, the climber's characteristics without human intervention and inherent bias of observation. One significant advantage of movement pattern clustering is that no *a priori* assumptions about the structure of the dataset are required to identify similar patterns; there were no *a priori* assumptions about transfer of experience induced in the statistical analysis. Our cluster hierarchical analysis used the squared Euclidean distance dissimilarity measure (for the intra-distance cluster) and the Ward linkage method (for the inter-cluster distance) (as used before by Schorer, Baker, Fath, & Jaitner, 2007; Seifert, Leblanc et al., 2011a). Twenty two variables were used to classify the participants: in-phase, out-of-phase modes of relative phase, mean and standard deviation of relative phase, horizontal, obliquely, vertical, crossed angular positions of both ice tools and crampons, mean and standard deviation of angular positions of both ice tools and crampons, the ratio between ice tool swinging and hole hooking, the ratio between crampon kicking and hole hooking, the ratio between repetitive ice tool swinging and definitive anchorage, the ratio between repetitive crampon kicking and definitive anchorage. The results of the cluster analysis were described as a dendrogram.

Next, the clustering analysis was validated by two methods. First, in line with methods of Breiman (1996), Duda et al. (2001), Rein et al. (2010) and Rein et al. (2010), the number of cluster and classification of a participant in a cluster were validated by a bagging procedure. A bagging is a bootstrapping procedure and consists of repeating cluster hierarchical analysis several times while excluding a different variable or a different participant each time and then determining whether the obtained clusters are stable. Stability was assessed by the number of turnovers, i.e., number of participants switching from one cluster to another cluster. The higher the number of turnovers when a variable is removed, the more important is this variable for the clustering. Second, to validate the clustering, Fisher information was calculated separately on the 22 variables to determine the most significant one. Fisher information corresponds to the ratio between inter-cluster and intra-cluster distances:

$$\text{Fisher information} = J_b/J_w \quad (5)$$

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Inter-cluster distances (J_b) corresponds to:

$$J_b = \sum_g N_g d^2(\mu_g, \overline{X}) \quad (6)$$

where N_g is the number of elements in the cluster g, d is the chosen distance, μ_g is the centre of cluster g (i.e. the mean of all points in g), $\overline{X}$ is the centre of all the points (i.e. mean of all the points).Intra-cluster distances (J_w) corresponds to:

$$J_w = \sum_g \sum_{i \in C_g} d^2(x_i, \mu_g) \quad (7)$$

where C_g are the points in cluster g, x_i is the value for each point.

The higher the Fisher value, the more discriminative are the variables. The cluster analysis was stable for a Fisher value > 1, meaning that inter-cluster distances were higher than intra-cluster distances (see Seifert, Leblanc et al. (2011a) for an example to analyze inter-individual variability in unskilled swimmers).

Finally, performance outcomes and measures of climbing movement fluency were compared between clusters by Kruskal-Wallis tests. Statistics were completed with Matlab 7.7.0.471® (The MathWorks Inc., U.S., R2008b) with a statistical significance level of $p < .05$.

3. Results

3.1. Inter-limb coordination and affordances detection

As observed in Fig. 4, the dendrogram distinguished three clusters: (i) Cluster 1 could be labelled "experienced climbers" composed by the five participants with an intermediate ability in rock climbing. This cluster showed the highest levels of variability in the relative phase of upper-lower limb coordination (standard deviation of $\phi(t) = 46.4°$), the upper limb angles (standard deviation of 33.3°) and lower limb angles (standard deviation of 30.3°). These climbers displayed the largest range of inter-limb coordination patterns in the sample (Table 1); (ii) Cluster 2 could be termed "medium climbing ability level", composed of eight participants with a medium level of variability in the relative phase of upper-lower limbs (standard deviation of $\phi(t) = 49.3°$), and the upper limb angles (standard deviation of 36.5°) and lower limb angles (standard deviation of 37.7°). Climbers of clusters 1 and 2 were characterised by low ratios between the frequency of ice tool swinging and definitive anchorage, and between the frequency of crampon kicking and definitive anchorage (i.e., 1 swinging for every

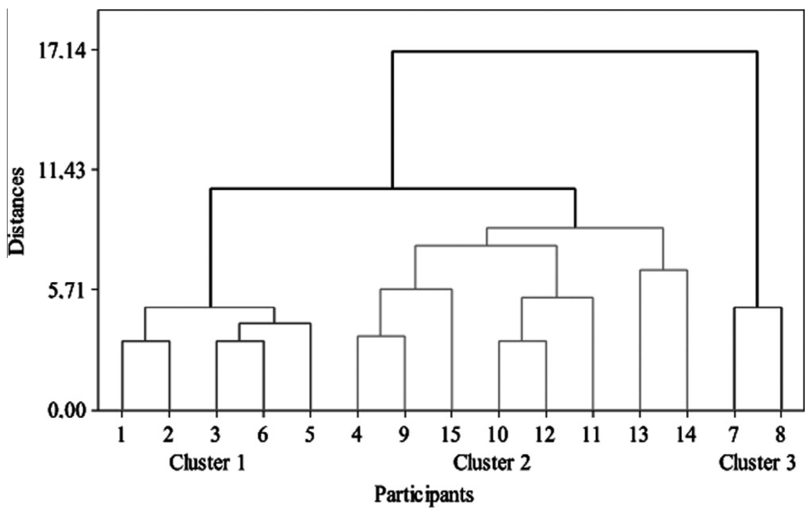

Fig. 4. Dendrogram showing the three clusters according to distance between participants. According to Fisher information, this clustering was confirmed by the ratio between inter-cluster distances and intra-cluster distances.

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2 anchorages) (Table 1); and (iii), Cluster 3 could be labelled "non-fluent climbers", composed of two participants with the lowest range of inter-limb coordination patterns; notably they spent the longest time in an in-phase coupling mode (~60% of time *vs.* ~30% of time for the two other clusters). They also exhibited the lowest levels of variability of upper-lower limb relative phase (standard deviation of $\phi(t) = 34.5°$), and upper limb angles (standard deviation of 26.8°) and lower limb angles (standard deviation of 11.7°) (Table 1). The most recurrent angular location of their ice tools (76% of time) and their crampons (89% of time) was oblique. Unlike individuals in the other two clusters, participants in this cluster tended to swing their ice tools and kick their crampons at least 1.4 times before gaining a definitive anchorage. Finally, the three clusters showed a higher number of ice tool swinging than hole hooking actions (ice tools swinging to hooking ratio was >3.5) and they also exhibited one ice tool action for every crampon action (Table 1).

The cluster validation procedure showed stability in the number of clusters and the cluster composition. Indeed, the Fisher value was >1 for 10 variables, suggesting that 10 variables significantly contributed to classify the participants (Table 1). These 10 variables were also those which led to turnovers when the bagging method was applied (Table 1). The bagging method showed (i) 32 turnovers when one variable of the 22 variables was removed each time and (ii) 23 turnovers when a different participant of the 15 participants was removed each time. Considering that 150 turnovers were possible (10 significant variables × 15 participants), the number of turnovers for the variables represented 21.3% and 15.3% for the participants.

4. Performance outcome and fluency of climbing movement

Kruskal-Wallis tests indicated significant differences in the vertical distance climbed in 5 minutes between the three clusters (17.8 ± 2.8 m for cluster 1, 10.6 ± 2.3 m for cluster 2, 3.0 ± 0.6 m for cluster 3; $H_2 = 8.18$, $p < 0.05$). Analysis of the pelvis vertical displacement-time curve showed a similar number of plateaux for the three clusters (respectively, 24.0 ± 5.1, 25.8 ± 2.7 and 22.0 ± 1.4), but shorter time durations per plateau for participants in cluster 1 than in clusters 2 and 3 (respectively, 5.8 ± 0.5 s and 7.1 ± 1.1 s *vs.* 10.7 ± 0.9 s; $H_2 = 6.73$, $p < 0.05$), suggesting that the latter cluster exhibited a lower level of climbing movement fluency.

5. Discussion

Our main findings revealed positive effects of previous experience in rock climbing on performance outcomes, climbing movement fluency and, more broadly, on movement coordination tendencies in participants climbing ice falls. In fact, what was transferred between the tasks, was not only one coordination pattern from rock climbing, but also an entire dynamics of coordination (see Kelso & Zanone, 2002). Indeed, our results showed that climbing movement fluency, the range and variability of the angular location of the limbs and the movement coordination pattern were higher in the group of rock climbers. In particular, when a comparison was undertaken between participants with previous rock climbing experience (cluster 1, considered as the most efficient) and participants in the two other clusters, three characteristics of the transfer of experience from rock to ice climbing could be observed: (i) better climbing movement fluency since the climbers of cluster 1 achieved a greater value for pelvis vertical distance in 5 minutes of ascent and they spent less time without any pelvis vertical displacements than participants of clusters 2 and 3, (ii) a higher perception of affordances, exemplified by calculations showing that climbers of cluster 1 achieved a lower ratio between the number of ice tool swings and definitive anchorages than participants of cluster 3, (iii) a larger range of inter-limb coordination patterns and angular locations of limbs than participants of clusters 2 and 3.

6. Climbing movement fluency and affordances

According to data of Cordier et al. (1996), who showed the acceleration of the body centre of mass as harmonic in experts and stochastic in beginners during rock climbing, our sample of novice ice climbers did not show homogeneous and fluent vertical pelvis displacement, since a frequent

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Table 1
Variables of the three clusters of climbers: Cluster 1 corresponds to 'Experienced climbers'; Cluster 2 corresponds to 'Medium climbing ability level'; Cluster 3 corresponds to 'Non-fluent climbers'. The Fisher information and results of the bagging procedure (i.e., number of turnovers) enabled to rank the ten most discriminative variables to classify the participants (highlighted in grey).

Variables	Cluster 1 $n = 5$	Cluster 2 $n = 8$	Cluster 3 $n = 2$	Fisher Information	Bagging (number of turnovers)	Variable ranking
Upper-lower limb coordination:						
ϕ (t) [-22.5°;22.5°]	32.9	28.7	57.9	2.8	5	2
ϕ (t) [-45°;-22.6°] and [22.6°;45°]	26.7	25.5	22.8	1.3	1	9
ϕ (t) [-77.5°;-45.1°] and [45.1°;77.5°]	31.1	33.9	14.7	2.3	3	6
ϕ (t) [-90°;-77.6°] and [77.6°;90°]	9.3	11.9	4.7	0.8	0	
Mean ϕ (t) in °	0.1	-3.3	-1.5	0.1	0	
Standard deviation of ϕ (t) in °	46.4	49.3	34.5	2.6	4	4
Upper-limb coordination:						
Ice tools horizontally located (% of time)	12.7	21.0	8.8	0.7	0	
Ice tools vertically located (% of time)	1.9	3.4	0.9	0.4	0	
Ice tools obliquely located (% ot time)	63.7	58.1	75.7	1.2	1	10
Ice tools crossed (% of time)	0.0	0.3	0.0	0.1	0	
Mean angle of ice tools (% of time)	16.1	-4.4	31.8	0.7	0	
Standard deviation of angle of ice tools (% of time)	33.3	36.5	26.8	0.8	0	
Lower-limb coordination:						
Crampons horizontally located (% of time)	34.2	38.6	10.8	1.9	2	7
Crampons vertically located (% of time)	0.3	1.6	0.0	0.4	0	
Crampons obliquely located (% of time)	65.5	58.8	89.2	2.4	5	5
Crampons crossed (% of time)	0.0	1.0	0.0	0.1	0	
Mean angle of crampons (% of time)	17.8	5.7	38.7	1.4	2	8
Standard deviation of agle of crampons (% of time)	30.3	37.7	11.7	2.6	4	3
Affordances (ratio between different types of action):						
Ice tools swinging / Definitive anchorage	0.5	0.7	1.6	2.8	5	1
Crampons kicking / Definitive anchorage	0.3	0.8	1.4	0.9	0	
Ice tools swinging / Ice tools hooking	3.7	9.5	3.6	0.2	0	
Ice tools anchorage / Crampons anchorage	1.0	1.0	1.3	0.2	0	

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alternation between climbs and pauses (i.e., plateaux) was observed. However, climbers of cluster 1, with an intermediate ability in rock climbing, showed the shortest plateaux duration suggesting a better individual-environment coupling. For instance, in rock climbing Sibella et al. (2007) emphasized the relationship between the lower geometric entropy index from the 3D body centre of mass displacement and the capacity of the rock climbers to move by using less than three holds. As stated previously, the 'three-holds-rule' could be used to determine whether rock climbers pick up affordance by touching a smaller number of holds before grasping the definitive hold to climb up. Therefore, if the number of touched holds is equal to or greater than three, it is more likely that the climber did not pick up affordances effectively, resulting in him climbing slowly, because his/her equilibrium is always maintained under control (Sibella et al., 2007). Our findings were similar, since participants with rock climbing experience (cluster 1) and participants of cluster 2 (who showed a similar level of climbing movement fluency as cluster 1) realised 1 ice tool swinging action for every 2 definitive anchorages, supporting their capability of perceiving affordances. Indeed, analysis of video footage revealed that the climbers with rock climbing experience swung their ice tools into existing holes in the ice surface so that the blade penetrated deeply at the first swing. According to the conceptualisation of Withagen, de Poel, Araújo, and Pepping (2012) the holes in the icefall correspond to affordances since they "invited behaviors" of participants with previous experience of climbing. Conversely, participants with the lowest climbing movement fluency (cluster 3) swung their ice tools and kicked their crampons at least 3 times before gaining a definitive anchorage because they did not use the existing holes of the ice fall. Instead they tried to create their own holes by engaging in repetitive ice tool swinging and crampon kicking. The behavioral responses observed in individuals of cluster 3 suggested a relative independence of the participant from the icefall properties, the latter not being perceived as affordances, since the climbers needed several swings of the ice tool or kicks with the crampons before deciding that an anchorage was stable.

7. Inter-limb coordination and angular limb location

A larger range and variability of inter-limb coordination patterns and angular locations of their limbs characterised the participants of cluster 1 with rock climbing experience. This larger range of movement patterns comes from the tendency to move the body from side to side like a door which opens and closes and a pendulum which oscillates. Rock climbers have experienced the use of gravity as an external force which can accelerate the body in the selected manner by the tendency to use oblique and vertical limb angular positioning. Conversely, the novice climbers of cluster 2, and in a more pronounced way, those of cluster 3, failed to exhibit lateral and oscillating body movements to get equilibrium under control (Bourdin et al., 1999; Testa, Martin, & Debu, 1999). They tended to freeze their motor system degrees of freedom through an in-phase mode of inter-limb coordination and displayed a reliance on horizontal or oblique angular locations for their limbs. Freezing the degrees of freedom of the musculoskeletal system is a typical characteristic of a novice performer (see Seifert, Leblanc, Chollet, & Delignières, 2010 for data in swimming; Vereijken, van Emmerik, Whiting, & Newell, 1992 in a ski-simulator task) preventing them from exploring action possibilities offered by the environment. Additionally, participants with rock climbing experience were able to further vary their limb angular locations and coordination pattern throughout the ascent, signalling their capacity to functionally and more efficiently interact with task and environmental constraints (Davids, Glazier, Araújo, & Bartlett, 2003; Glazier, Wheat, Pease, & Bartlett, 2006). Fig. 5 exemplifies the relationships between the limb angular locations-time curve and the vertical pelvis displacement-time curve for an exemplar participant in each cluster. These data illustrate that, the higher the range and the variability of the angular locations of the limbs, the greater was climbing movement fluency and performance outcomes.

8. Specific skills of ice climbing

Last, even if some rock climbing skills were transferred to the ice climbing performance context, some characteristics demonstrated that the climbing skills of the whole sample of novice ice climbers

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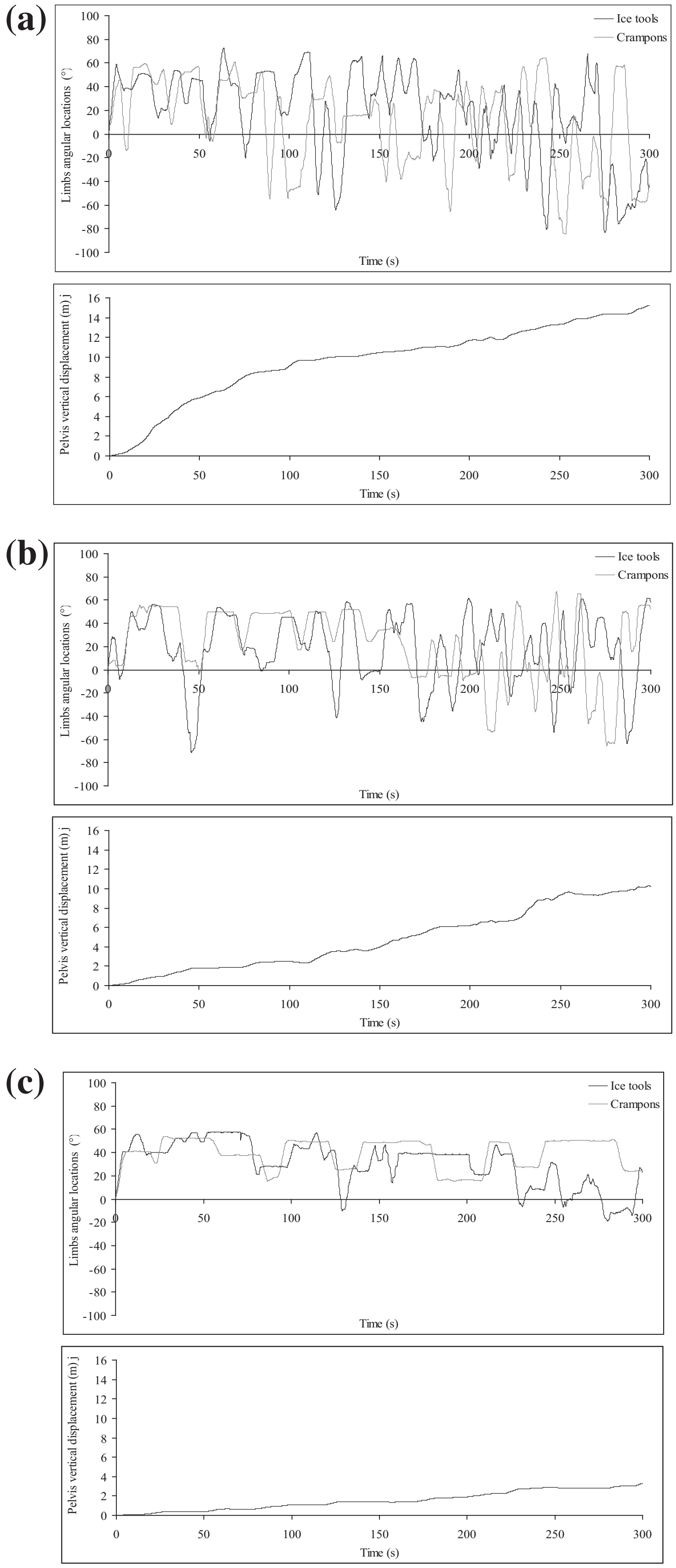

Fig. 5. Relationships between limbs angular locations-time curve (top panel: upper limbs in black and lower limbs in grey) and vertical pelvis displacement-time curve (down panel) for a participant of each cluster: (a) Participant 1 in cluster 1, (b) Participant 9 in cluster 2, (c) Participant 7 in cluster 3. This figure shows that low range and variability of limbs angular locations were associated to low vertical pelvis displacement and similarly non-fluent climbing.

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in this study differed to expert ice climbers. In particular, our novice ice climbers favoured using ice tools actions rather than crampon actions (evidenced by the ratio between ice tool and crampon actions). Indeed, in contrast to expert climbers who typically needed just one swing of the ice tool for every two kicks of the crampon (eigen-frequency ratio of 1:2) (Seifert, Wattebled et al., 2011b), all our novices relied on one ice tool action for every crampon action (eigen-frequency ratio of 1:1) (Table 1). These data suggest that ice climbing for novices corresponded to a basic coordination pattern such as climbing a ladder.

Moreover, our results showed that, regardless of cluster, novice ice climbers favoured the action of ice tool swinging rather than hole hooking (i.e., the ratio between ice tool swinging/hooking was >3.5; see Table 1). Conversely, Seifert, Wattebled et al. (2011b) reported a ratio between ice tool swinging/hooking equal to .5 for expert climbers, supporting bi-stability of types of actions (i.e., ice tool hooking and swinging). Unlike experts who are able to accurately perceive existing holes in the icefall in order to hook them (an energy efficient strategy) or to create their own holes when the ice fall texture was dense, our data on novice performance suggested that they perceived the affordance of the ice tool to be more like a hammer and not a hook.

9. Conclusion

Data on climbing movement fluency, affordance detection (i.e., types of action), range and variability of limb angular locations and movement coordination patterns exemplified the propensity of neurobiological complex systems to shape stable movement patterns in one region of the perceptual-motor landscape of performance (i.e., ice climbing) based on those existing in another region, gained through different experiences (i.e., rock climbing). This suggestion is based on the integration of a variety of information sources that exist both in rock and ice climbing performance environments, acting as affordances, and which can constrain motor behaviors of performers. These information sources include prior experiences in rock climbing such as quadrupedal locomotion in the vertical plane using various limb angular locations, the respect of the 'three-holds-rule', and alternation of body equilibrium control and limb movements to climb upwards. These characteristics led us to consider the transfer of previous experiences as adaptive, functional and efficient because the individuals were able to reinvest movement coordination patterns from a pre-existing repertoire. The data also provided insights into the processes of experience transfer in which performers adapted their entire coordination dynamics according to the interacting ecological constraints they encountered (i.e., perceiving affordances). Finally, the use of ice tools and crampons is specific to ice climbing and result in certain types of emergent behaviors (i.e., swinging *vs.* hooking) that can neither be experienced, nor transferred, from the dynamic performance context of rock climbing. The specificity of these tools led novices to favour ice tool actions rather than crampon actions because they were able to use ice tools as a hammer.

Conflict of interest statement

No conflict of interest.

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