Analysis of relations between spatiotemporal movement regulation and performance of discrete actions reveals functionality in skilled climbing

ORTH, Dominic, KERR, Graham, DAVIDS, Keith <http://orcid.org/0000-0003-1398-6123> and SEIFERT, Ludovic

Published version

ORTH, Dominic, KERR, Graham, DAVIDS, Keith and SEIFERT, Ludovic (2017). Analysis of relations between spatiotemporal movement regulation and performance of discrete actions reveals functionality in skilled climbing. Frontiers in Psychology, 8 (OCT).

A review of relationships between spatiotemporal movement regulation and discrete actions for revealing functionality of skilled climbing

Activity states and performance during climbing

Type: Review

Author List: Dominic Orth[1,2], Graham Kerr[2,3], Keith Davids[4], Ludovic Seifert[1]

Affiliations:
[1] CETAPS - EA 3832, Faculty of Sport Sciences, University of Rouen, France.
[2] School of Exercise and Nutrition Science, Queensland University of Technology, Brisbane, Australia.

[3] Movement Neuroscience Program, Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia.

[4] Centre for Sports Engineering Research, Sheffield Hallam University, Sheffield, United Kingdom.

Corresponding author:
Ludovic SEIFERT CETAPS EA3832 Faculty of Sports Sciences, University of Rouen Normandy Boulevard Siegfried 76821 Mont Saint Aignan cedex, France E-mail: ludovic.seifert@univ-rouen.fr Tel: (+33) 235 146 784 Fax: (+33) 235 147 793

Funding
This project received the support of the CPER/GRR1880 Logistic, Mobility and Numeric and funding from the French National Agency of Research (reference: ANR-13-JSH2-0004 DynaMov).

Conflicts of Interest
Dominic Orth, Graham Kerr, Keith Davids and Ludovic Seifert declare that they have no conflict of interest with the content of this review. Neither in terms of payment or services from a third party, influence from any funding bodies or other possible relationships. No patents or copyrights are related to this work.

Abstract

In this review of research on climbing expertise, we focus on different measures of climbing performance, including spatiotemporal measures related to fluency and activity states (i.e., discrete actions), performed by climbers toward achieving the overall goal of getting to the end of a route efficiently and safely. Currently a broad range of variables have been reported, however, many of these fail to capture how climbers adapt to a route whilst climbing. We argue that spatiotemporal measures should be considered concurrent with evaluation of activity states (such as reaching or exploring) in order gain a more comprehensive picture of how climbers successfully adapt to a route. Spatial and temporal movement measures taken at the hip are a traditional means of assessing efficiency of climbing behaviors. More recently, performatory and exploratory actions of the limbs have been used in combination with spatiotemporal indicators, highlighting the influence of limb states on climbing efficiency and skill transfer. However, only a few studies have attempted to combine spatiotemporal and activity state measures taken during route climbing. This review brings together existing approaches for observing climbing skill at outcome (i.e., spatiotemporal assessments) and limb (i.e., activity states) levels of analysis. Skill level is associated with a spatially efficient route progression and lower levels of immobility. However, more difficult hold architecture requires significantly greater mobility and more complex movement patterning to maintain performance. Different forms of functional, or goal-supportive, movement variability including active recovery and hold exploration, have been implicated as important adaptations to physiological and environmental dynamics that emerge during the act of climbing. Indeed, recently it has also been shown that when climbing on new routes, efficient exploration can improve the transfer of skill. Ultimately, this review provides insight into how climbing performance and related actions can be quantified to better capture the functional role of movement variability.

Key words: affordances, exploration, functional movement variability, rock climbing, motor skill, skill transfer

1. Introduction

Traditionally, skilled climbing is characterized by the efficiency of spatial and temporal patterns that emerge at the centre of mass (COM) during the act of climbing (Billat, Palleja, Charlaix, Rizzardo, & Janel, 1995; Cordier, Dietrich, & Pailhous, 1996). Temporal assessment quantifies the number and nature of stoppages relative to continuous climbing, indicating the amount of time spent in isometric contraction (Billat et al., 1995; White & Olsen, 2010). Spatial indicators highlight the efficiency of a climber's trajectory across the surface, estimating the ability to perceive an efficient ‘pathway’ through the route (Boschker & Bakker, 2002; Cordier, Mendès-France, Bolon, & Pailhous, 1993). Finally, combined spatiotemporal measures, such as the minimization of jerk, globally indicate how smoothly climbing movements are linked together (Seifert, Orth, et al., 2014). Importantly, evaluating performance along spatial and temporal variables can address different mechanisms underpinning skilled climbing (Cordier et al., 1996). For example, initial and rapid improvement in performance is believed to be primarily influenced by the rapidly adapting visual-motor system (Pezzulo, Barca, Bocconi, & Borghi, 2010). Alternatively, a climber may improve performance by linking movements in a more periodic fashion. These sorts of improvement occur over longer time-scales, such as the months and years required for musculoskeletal system adaptation (Vigouroux & Quaine, 2006).

More recently, activity states such as reaching and grasping have been distinguished as having explorative (information gathering) or performatory (body progressing) qualities, providing an estimate of the intentions underpinning an individual’s actions during climbing (Pijpers, Oudejans, Bakker, & Beek, 2006). For example, changing constraints, such as height from the ground during climbing practice (Pijpers et al., 2006), does not physically modify climbing affordances. Where climbing affordances are defined as opportunities for qualitatively distinct actions that support climbing such as hold reachability, grasp-ability, stand on-ability and specific climbing movements (Boschker, Bakker, & Michaels, 2002). However, increasing climbing height can interact with an individual’s state. This can alter the discrete actions used during climbing, but, in a transient fashion on the basis of altered intentions brought about by an increased state of anxiety. In this case, an increased state of anxiety, influences intentions toward information pick-up for remaining fixed to the wall, as opposed to achieving progression. Such inferences of climbers intentions are generally based on behavioral data. For example, when an individual reduces the distance they are willing to reach for grasping holds, or they increase their use of exploratory actions, this suggests the climber is primarily concerned with stability as opposed to efficient progression (Pijpers et al., 2006; Seifert, Wattebled, et al., 2014).

A limitation in the extant literature is that how an individual’s specific activity state can influence climbing efficiency is poorly understood, and, being able to combine these measures can be tremendously informative (Orth, Davids, & Seifert, 2016). Indeed, approaches that have considered these variables in combination have uncovered important insights into the functional or goal-supportive characteristics of movement variability (Fryer et al., 2012; Seifert, Boulanger, Orth, & Davids, 2015). For instance, Pijpers et al. (2006) implied that exploratory behavior reflects poor performance. Whereas, more recent studies have combined the analysis of exploratory actions with spatiotemporal performance outcomes, revealing that exploratory actions can be related to an improvement in performance through practice (Seifert et al., 2015). Thus, this review draws together studies that have reported on performance and discrete limb actions in climbing tasks to evaluate how, in combination, these can explain successful and efficient climbing. The review is structured into three parts. First, we examine the existing state of the art on how spatial and temporal outcomes are used to quantify skilled climbing. Next, data pertaining to activity states are considered with respect to their functionality for the individual. Finally, hypotheses are presented for how activity states combined with spatial-temporal outcomes can indicate specific intentions of climbers during the act of climbing.

2. Search methodology

Medline and SPORTDiscus databases were searched for published primary sources. Keywords related to climbing (rock climbing, ice climbing, mountain climbing, boulder climbing, artificial climbing, top-rope climbing, lead-rope climbing, mixed climbing, indoor climbing, outdoor climbing, route climbing, slope climbing) were pooled (via Boolean operation ‘OR’) and combined (via Boolean operation ‘AND’) with keywords related to skilled behavior (skill, transfer, perform, ability, expert, novice, beginner, intermediate, advanced, elite, dynamic, force, kinematics, kinetics, perception, action, cognition, behavior, centre of mass, trajectory, movement, movement pattern, recall, gaze, vision, coordination, motor, feet, hand, foot, grasp, reach, pattern, intervention, pedagogy, feedback, constraint, coach, learn, practice, applied, train, fluency, fluidity, smoothness, jerk, activity state, classification, intention, exploration, strategy) and also pooled via Boolean operation ‘OR’. Results were limited to human participants, written in the English language, and, Medline and SPORTDiscuss databases searched from their earliest available record up to November 2016. Google Scholar was then used to scrutinize the related articles and referencing studies. Reference lists were of all eligible studies were then inspected by hand.

Articles were restricted to those written in English. Restrictions were also made on the participant sample, study design and outcomes measures. Specifically, for inclusion, studies were required to report sample characteristics so that ability level could be estimated such as either as, beginner, intermediate, advanced, elite or upper elite (Draper, Canalejo, et al., 2011). Study designs were limited to experimental or technical reports that involved climbing a surface graded for difficulty (Draper, Canalejo, et al., 2011). Furthermore studies where the task goal did not, implicitly or otherwise, require getting to the end of the route were excluded. For example if the task required participants adopt a static posture or perform isolated reach and grasp actions, it was excluded since such task constraints do not impose a route finding problem. Outcomes were restricted to at least one measure to quantify spatial, temporal patterns of the COM or limbs, or, activity state during actual climbing. Appraisal of article quality, was evaluated in terms of potential contribution to understanding how activity states influence performance efficiency along spatial-temporal measures. Eligible experiments were then identified to a standardised form which was then used to extract relevant study data (see Table 1). These included, experimental design, sample characteristics, interventions (including detailed characteristics of route design properties), task characteristics, independent variables and levels, outcome measures, and comparisons and interaction effects.

3. Results

Using the search methodology, the Medline database yielded 1099 titles and abstracts. These were screened yielding 35 relevant articles, which were identified and their full texts retrieved. Relevant studies were then screened using the standardized inclusion criteria and 13 eligible studies identified. Using the same search methodology, the SPORTDiscsuss database was searched. This yielded 2201 results, these titles and abstracts were screened, from which 59 relevant articles were identified. After duplicate removal, full texts were retrieved and eligibility was assessed using the standardized inclusion criteria, identifying 15 studies this way. The related articles, citing articles and reference lists of 7400 eligible studies were searched using Google Scholar. 94 relevant studies were subsequently identified for eligibility screening. After duplicates were removed, an additional 13 eligible studies were identified this way. The article search was stopped at this point. From this pool of 41 studies, 22 fulfilled the eligibility criteria. These are summarised to Table 1 and discussed below.

>>>Table 1 here<<<

4. Spatial and temporal measures of skilled adaptation to route properties in climbing

Data on skilled climbing behavior can reflect coordination of actions to route properties, providing insights on the quality of movement adaptations. A number of studies have incorporated spatial and temporal measures into a single outcome to quantify climbing fluency. These have generally involved the analyses of the climbers' COM projection, to estimate velocity (Cordier et al., 1996; Sibella, Frosio, Schena, & Borghese, 2007), acceleration (Cordier et al., 1996; Sibella et al., 2007), jerk (Seifert, Orth, et al., 2014), and phase portrait patterning (Cordier et al., 1996). Among these, being very much linked to the number sub-movements used in carrying out an action (Elliott et al., 2010), jerk cofficients on hip movements provides the most straightforward indication of capacity to co-adapt spatial-temporal demands of performance (Seifert, Orth, et al., 2014). For example, Seifert et al. (2014) calculated jerk coefficients on three dimensional hip translation and rotation accelerations. Here, jerk coefficients improved with practice on a route that involved use of different types of grasping techniques (overhand grasping and pinch grips), compared to no significant change on a route that required use of a single type of action (overhand grasping) (Seifert, Orth, et al., 2014).

Whilst expertise in climbing involves highly adaptive and proficient performance along both spatial and temporal dimensions in combination, current understanding of skill and practice effects has been primarily approached by considering each dimension separately (Cordier et al., 1996; Sibella et al., 2007).

4.1 Spatial indicators of climbing fluency

Spatial indicators relate to analyses of displacement on a surface. Existing approaches include computation of the geometric index of entropy (GIE, see equation 1 below) (Boschker & Bakker, 2002; Cordier et al., 1993; Cordier, Mendès-France, Bolon, & Pailhous, 1994; Cordier, Mendès-France, Pailhous, & Bolon, 1994; Orth, Button, Davids, & Seifert, 2017; Pijpers, Oudejans, Holsheimer, & Bakker, 2003; Sanchez, Boschker, & Llewellyn, 2010; Seifert et al., 2015; Sibella et al., 2007; Watts, Drum, Kilgas, & Phillips, 2016), climb distance (Green, Draper, & Helton, 2014; Green & Helton, 2011; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013), average movement distance (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008), COM-to-wall distance (Zampagni, Brigadoi, Schena, Tosi, & Ivanenko, 2011), and planar displacement of the COM (Zampagni et al., 2011). Interpreting the quality of displacement with respect to a route is the main reason GIE has enjoyed widespread application (Boschker & Bakker, 2002; Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994; Pijpers et al., 2003; Sanchez et al., 2010; Seifert, Orth, Button, Brymer, & Davids, 2017; Sibella et al., 2007).

Specifically, GIE is given for a given trajectory $x : [O, T] \to R^3$, letting Δx be the trajectory length (Equation 1) and $\Delta c(x)$ the convex hull parameter. The GIE is given by:

$$\Delta x = \sum_{i=1}^{N} \sqrt{x_i^2 + y_i^2}$$

Equation 1

$$GIE_x = \frac{\log(2 * \Delta x) - \log(\Delta c(x))}{\log(2)}$$

Equation 2

According to Cordier et al. (1994) the GIE can assess the amount of fluency of a curve. The higher the entropy value, the higher the irregularity of the climbing trajectory, whereas the lower the entropy value, the more regular is the climbed trajectory. GIE has a number of advantages over reported spatial variables, such as the average movement distance (Nieuwenhuys et al., 2008), in that it is based on theoretically generalizable principles (Cordier, Mendès-France, Pailhous, et al., 1994), readily interpreted with respect to climbing activity, and, is effective for detecting skill (Cordier et al., 1993), practice (Cordier et al., 1993), route (Seifert et al., 2017) and technique effects (Boschker & Bakker, 2002; Sibella et al., 2007). Furthermore, data collection to perform an entropy calculation is highly feasible involving use of a single camera (Sanchez et al., 2010). Figure 1 shows how entropy is calculated (Panel A) and with respect to how changing the length of an analysed trajectory with the convex hull affects outcomes.

In climbing tasks, entropy outcomes are particularly increased when route difficulty is hard relative to the ability level of the climber, sometimes referred to as functional task difficulty (Guadagnoli & Lee, 2004), and, the route has not yet been physically practiced (Cordier, Mendès-France, Pailhous, et al., 1994). For example, when the functional difficulty of a route is increased, by modifying the number of choices embedded into it, entropy increases even in experienced climbers (Seifert et al., 2015). Practice effects have also been reported, with performance after repeated practice generally converging to an asymptote level at a rate dependent on the initial skill level of the climbers. Typically, the higher the initial skill level, the more rapid an asymptote is reached (Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et al., 1994). Intriguingly, Boschker and Bakker (2002) found that prior knowledge about advanced inter-limb coordination patterns can improve entropy in beginners, allowing them to improve performance faster through practice, see also (Seifert, Coeurjolly, Hérault, Wattebled, & Davids, 2013).

Notably in Boschker and Bakker (2002), practice of less advanced techniques also resulted in entropy values similar to those when advanced actions were used, suggesting that the route designs may not have required more advanced technique for improved performance. Sanchez et al. (2010) also raised the concern, that, when elite climbers were compared on routes close to the limits of their ability level, no relationship between the climbers' performance GIE was shown. This may have been because the climbers had not practised physically on the wall before testing began, and, the difficulty was close to the climbers' ability limit (Sanchez et al., 2010, p. 360). Implications of these studies suggest that, through observing repeated practice, larger learning effects can be expected when route difficulty is closer to a climber’s ability level (Cordier et al., 1993). It is worth emphasizing, however, that these findings also indicate that in some cases a higher entropy may not necessarily indicate poor performance (Davids et al., 2014).

>>Figure 1 about here<<

Aside from cases where task and skill interaction effects make entropy difficult to interpret, the variable is limited in other ways. Currently the application of GIE is limited to a single plane of analysis and important anterior-posterior plane translations (Robert, Rouard, & Seifert, 2013; Russell, Zirker, & Blemker, 2012; Sibella et al., 2007; Zampagni et al., 2011) or rotations around any given axis are missed (Seifert et al., 2015; Seifert, Orth, et al., 2014). Of additional concern, is that if a climber is 'blocked' at certain points in the climb, the GIE magnitude will only be influenced if there is an increase in the length of the trajectory during this time. For example this can occur when postural readjustments are made. If no movement at the hip occurs during a stoppage, however, GIE magnitude will not be affected (Watts et al., 2016). Thus, changes in constraints, such as the use of a top-rope (a rope is secured to the top of the route prior to performance) verse lead roping (where the climber needs to secure the rope to multiple fixed points during climbing for safety), may not lead to significant differences in entropy because they do not require a significant reorganisation of the pathway taken through the route (cf. Hardy & Hutchinson, 2007). None-the-less, GIE is a highly usable method, where limitations are made up for in ease of acquisition and interpretation.

4.2 Temporal indicators of fluency

Temporal measures interpreted with respect to continuity of climbing performance include the: (i) relationship between static and dynamic movements at the hips (Billat et al., 1995; Cordier, Mendès-France, Bolon, et al., 1994; Nieuwenhuys et al., 2008; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013; White & Olsen, 2010); (ii) relationship between hold grasping and moving between holds (Nieuwenhuys et al., 2008; Pijpers, Oudejans, & Bakker, 2005; Pijpers et al., 2006; White & Olsen, 2010); (iii) plateau duration at the hips (Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013); (iv) within-route climb time (Draper, Dickson, Fryer, & Blackwell, 2011; Sanchez et al., 2010; Seifert, Wattebled, et al., 2013); (v) time spent in three-hold support (Sibella et al., 2007) and; (vi) movement frequency (Cordier et al., 1996).

Quantifying the amount of time spent in different climbing-specific activity states provides one of the better time based indications of the climbers adaptation to route properties. For example, the degree of mobility is sensitive to local changes in the routes difficulty, including crux and rest points (Sanchez et al., 2010), and can detect differences between individuals who fall or complete the route (Draper, Dickson, et al., 2011). The most predominant approach to estimate performance in the temporal dimension is the computation immobility to mobility ratio, calculated by determining how long, with respect to the total climb time, an individual's COM or limbs remain in a stationary state relative to its moving state.

According to Billat et al. (1995) time spent immobile reflects time under isometric contraction, subsequently incurring an energy cost. However, since depending on the nature of the hand holds, this time can either increase fatigue in the finger muscles (Vigouroux & Quaine, 2006) or provide an opportunity to allow these muscles to recover (Sanchez, Lambert, Jones, & Llewellyn, 2012a), the characteristics of the route design needs to be addressed (for an innovative modelling approach see, Tosi, Ricci, Rosponi, & Schena, 2011). Indeed, it has been shown that periods of immobility can reflect strategic actions with respect to demands on the physiological system imposed by route design (Billat et al., 1995; White & Olsen, 2010). For example, different gripping techniques provide the possibility to vary the arm angle, which might afford more or less rest while grasping a hold and immobile (Amca, Vigouroux, Aritan, & Berton, 2012). This is also true in terms of the overall posture that climbers can adopt. For example, when sitting away from the wall with arms extended, passive forces can be exploited for remaining on the wall at a reduced energy cost (Russell et al., 2012; Zampagni et al., 2011).

Alternatively, White and Olson (2010) also speculated that a high immobility at the hip, in the case of bouldering, reflects an inability to perceive how to move through a route continuously, reducing performance in the activity. Sanchez et al. (2012a) provided some evidence for this argument, showing that more experienced climbers spent longer at rest locations within routes when not given an opportunity to view the route from the ground. This suggesting that immobility can indicate visual exploration of upcoming holds. Thus, individuals might benefit from periods of immobility at the hips and longer periods of reaching because exploratory actions might help to determine more effective pathways through the route (Nieuwenhuys et al., 2008; Sanchez et al., 2010; Seifert et al., 2015). Indeed, typically beginners show high levels of immobility, suggesting a lack of effective pick-up of information for perceiving climbing opportunities for route progression (Pijpers et al., 2005; Pijpers et al., 2006).

A key disadvantage of immobility is that classifying an individual as immobile is commonly undertaken by frame-by-frame analysis of an operator. For example, criteria for mobility have included statements like: “progress of the hips was observed” (Billat et al., 1995) whereas, criteria for static climbing have included: “no discernible movement in pelvic girdle” (White & Olsen, 2010). In an ice-climbing study, an automatic approach was taken by Seifert et al. (2014) using a definition based on a movement threshold. In this case, immobility was considered when, along the vertical axis, pelvis displacement was less than 0.15 m for durations longer than 30 s. This approach, however, required manual digitisation of the hips and was limited to analysis of vertical displacement actions of ice-climbers. Similar problems arise when manually coding limb states, where a limb is determined as moving between holds (mobile) or is in contact with a support surface (immobile) (Pijpers et al., 2006; White & Olsen, 2010). Thus, since immobility is generally determined as the lack of displacement over time, directly using velocity is a possible solution we suggest here. Specifically, for a trajectory $x : \lfloor O, T \rfloor \rightarrow R^3$, we find the thresh-hold based immobility to mobility ratio as:

$$IMR_x = \frac{\sum_{i=1}^{N} P_i}{N}$$

Equation 3

$$P_i = \begin{cases} 1, & if\ v_i < thresh \\ 0, & if\ v_i \geq thresh \end{cases}$$

Equation 4

$$v_i = f\sqrt{x_i^2 + y_i^2}$$

Equation 5

Of additional concern when using immobility is that the (ir)regularity in the temporal dynamics of movements are not considered (Seifert, Coeurjolly, et al., 2013). For example, a climber could remain immobile at single location on the wall, with the remaining climb time measured as mobile. Cordier et al. (1996), addressed this concern using a spectral dimension analysis of the last five practice trials (of ten) and showed that temporal movement dynamics of experts were periodic, since they displayed vertical displacement of the hips at regular intervals of 3 seconds. Furthermore, phase portrait analyses of each group revealed that advanced individuals displayed more regular movement characteristics (stable dynamics), whereas, intermediate climbers exhibited less predictable dynamics. These findings suggesting advanced climbers achieved a stable 'coupling' between their coordination repertoire and the environmental features. The temporal analyses used with reference to their GIE analysis (Cordier et al., 1996; Cordier et al., 1993), showed that whilst the intermediate climbers, achieved similar levels of GIE efficiency, relative to the advanced group, they still required more training to improve efficient temporal dynamics. Indeed, the major limitation of spatial and temporal measures is that, although they provide important information in isolation, interpreting the nature of movement adaptions during climbing can be enhanced by considering these outcomes in combination (Draper, Canalejo, et al., 2011; Laffaye, Collin, Levernier, & Padulo, 2014; Magiera et al., 2013; Seifert, Wattebled, et al., 2013).

4.3 Multi-variate approaches to understanding climbing fluency

Thus, we now consider in more detail how combined measures of spatial-temporal indicators of performance can improve interpretation of climbing behavior using exemplary data (Orth, Davids, & Seifert, 2014). In Figure 2, Panel A, both immobility (using equations 3, 4 and 5) and GIE (equations 1 and 2) are calculated on a climbed trajectory at three sections of a beginner level route (French rating scale of difficulty = 5a). It is shown that, depending on which section of the route the climber is in, the relationship between GIE and immobility can be inversed. Indeed, spatial and temporal properties of behavior are probably co-adapted depending on the constraints on performance (Billat et al., 1995). For example, when required to use complex movements, such as when using dynamic moves, a high degree of mobility is probably also important. Conversely, when using less dynamic movements, a low level of mobility may help maintain a degree of stability, particularly when needing to keep the COM close to the wall (Fuss, Weizman, Burr, & Niegl, 2013). If co-adaptation between GIE and IMR do support efficient climbing, a clear hypothesis is that immobility and movement complexity are co-adapted to maintain performance in terms of smoothness or jerk (Seifert et al., 2015; Seifert, Orth, et al., 2014).

>>Figure 2 about here<<

An important limitation in understanding the results related to performance fluency such as, Jerk, GIE and IMR, is that, without a consideration of the climbers intentions during periods of immobility or increased entropy, these data may be mistakenly concluded as dysfunctional (Seifert, Orth, et al., 2014). The study by Fryer and colleagues (2012) illustrates this point nicely. In this study more experienced climbers exhibited a *greater* percentage of time spent immobile, compared to less experienced individuals. After carrying out an activity analysis into the types of actions undertaken during rest, it was found that the more experienced climbers were actively resting during immobility, either applying chalk to their hands or shaking their hands. In this example, without additional data from the activity analysis, it may have been erroneously concluded that the climbers were stopping more due to the greater physiological demand imposed by the route. In actual fact, the data highlighted the climbers' self-management of their internal states, relative to their exploitation of opportunities for rest in the climbing route, an important skill-dependent performance behavior (Fryer et al., 2012). This case exemplifies how interpreting activity states of climbers can provide mechanistic insights of fluency measures (Seifert et al., 2015; Seifert, Coeurjolly, et al., 2013).

5. The role of activity states in climbing for understanding performance

It is generally assumed that the task goal corresponds to the intentions of the individual where in climbing, the goals of the task are to: a) not fall; b) get to the end of a route, and; c) use an efficient pathway and movement patterning that reduces prolonged pauses (Orth et al., 2016). However, importantly, intentions can be influenced by skill (Rietveld & Kiverstein, 2014), which are reflected in adaptations that emerge with respect to dynamic constraints (Balagué, Hristovski, & Aragonés, 2012; Davids, Araújo, Seifert, & Orth, 2015). Thus, estimates of the intentions of individuals during performance can help place performance outcomes more accurately in line with what an individual was trying to achieve.

Seifert et al. (2014), for example, showed that expert ice-climbers went about achieving their intentions to maintain energy and economy by focusing perception and action toward specific intentions. Actions were related to the perception of information for the usability of existing holes in the ice fall in so far that they tended to seek holds that did not require them to swing their ice tool. In contrast, the intentions of inexperienced climbers pertained to stability, where perceptions were focused on information related to the size of holes in the ice surface. In this case actions were motivated for achieving deep, secure, anchorages during ascent. Indeed, inexperienced climbers displayed significantly longer periods of immobility at the hips, higher amounts of swinging actions prior to making a definitive anchorage with their ice-tools, and tended to adopt a 'X-like' body position with the arms and legs spread out for stability. Whilst the inexperienced climbers showed poor performance in terms of temporal fluency, their exploratory actions were in correspondence to the intention to avoid falling. Thus, the distinction between exploratory and performatory actions is fundamental to understanding climber intentions and the functionality of their actions during performance and learning.

5.1 Performatory actions

According to Pijpers and colleagues (2006), performatory actions are meant to reach a specific goal and include: moving a hand or foot from one hold to the next to use it as support for further climbing actions (Nieuwenhuys et al., 2008; Pijpers et al., 2006; White & Olsen, 2010); using a hold to move the entire body vertically or ascend the route (Sanchez et al., 2012a; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013); using a hold to support recovery actions (Fryer et al., 2012; Sanchez et al., 2012a); and, making visual fixations during movement at the hips (Nieuwenhuys et al., 2008). Theoretically, performatory actions correspond to actions that are intended for progression. If performatory actions are effective they should improve fluency, by reducing the amount of time spent immobile and contributing to ongoing progression through the route. For example, a climber might skip holds, use a more difficult movement (Sibella et al., 2007) or use less advanced actions (Boschker & Bakker, 2002) which might result in more or less fluid climbing performance.

5.2 Exploratory actions

Exploratory actions, on the other hand, are primarily information gathering movements (Pijpers et al., 2006) where the type of information important to support perception of movement opportunities (i.e., affordances) can pertain to modalities such as haptic, auditory, visual and kinesthetic (Seifert, Wattebled, et al., 2014; Smyth & Waller, 1998). Exploratory actions have included: when climbers explore whether a hold is within reach (Pijpers et al., 2006); when a hold is touched without being used as a support (Nieuwenhuys et al., 2008; Pijpers et al., 2006; Sanchez et al., 2012a; Seifert, Orth, et al., 2014; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al., 2013); when an anchorage is weighted to test its fallibility (Seifert, Wattebled, et al., 2014); when tools are used to swing without a definite anchorage (Seifert, Wattebled, et al., 2014; Seifert, Wattebled, L'Hermette, & Herault, 2011; Seifert, Wattebled, et al., 2013); and when a visual fixation occur whilst an individual is immobile (Nieuwenhuys et al., 2008). When exploratory indices increase, this is generally associated with poorer performance on measures of fluency (Orth et al., 2016). For example, if a climber stops because they cannot perceive an effective path through the route (Cordier et al., 1993; Sanchez et al., 2012a), this would be associated with a higher frequency of hold exploration (Pijpers et al., 2006) and possibly an increased GIE (Cordier, Mendès-France, Pailhous, et al., 1994). Furthermore, as exploration reduces, fluency can improve (Seifert, Orth, et al., 2014; Seifert, Orth, Herault, & Davids, 2013), suggesting an important relationship between exploration and performance improvement through practice. For example Seifert et al. (2015) recently showed how exploration remained elevated under transfer conditions after a period of variable practice (i.e., where each training session involved practice on one of three different routes). In this study, implications were that potential mechanisms underpinning the positive transfer in climbing were related to the efficient use of exploration.

6. Variability in activity states and their functionality

In this final section, we explore some of the implications of linking different activity states with performance outcomes (summarized in Table 2) with predictions for future work. Specifically, we attempt to explain the goals or intentions underpinning behavioral variability related to both activity state and spatial-temporal measures. Indeed, a key result of this review has been the identification of a broad range of activity states that have been reported in the literature that appear to be important for performance during climbing. As clarified in Table 2, key activity states include: immobility; postural regulation; grasping; grip change; active recovery; reaching; reaching and withdrawing; traction; and, chaining movements in succession.

Typically, total immobility is a sign of poor performance (e.g., being ‘blocked’), however, functional movement variability can be identified in efforts to visually explore (such as indicated though head movements or gaze tracking tools). Postural exploration is probably particularly relevant for beginners, as this may allow an individual to determine more efficient positions and new body-wall orientations that may be important for more advanced movements (Seifert et al., 2015). Another possibility discussed, has been that the individual may benefit from immobility by visually exploring upcoming holds, perhaps indicated by the amount of fixations made and their relative distance to the individual during immobility (Sanchez et al., 2012a).

Exploration can also include reaching to touch a hold but not grasping it or using it to support the body weight (Seifert et al., 2015). This is probably important for perceiving accurate body-scaled actions (Pijpers, Oudejans, & Bakker, 2007). Perhaps, as different techniques, such as dynamic moves (Fuss et al., 2013), become part of an individual’s action capabilities this boundary of reachability may distinguish individuals of different skill levels. Making adjustments in how a hold is grasped prior to using it, is also a form of exploration in terms of its ‘grasp-ability’. Prior to applying force to a hold climbers can be seen, in some cases, to make adjustments to how they position their hand on a hold. Such exploratory actions may be important to improve the amount of friction that can be applied to the hold (Fuss et al., 2013), or, enable a qualitatively different way of using the hold such as in cases where multiple edge orientations are available (Seifert, Orth, et al., 2014).

*** Table 1 about here ***

Finally, It has been argued that exploration can support perception of affordances or opportunities for new climbing moves (Seifert, Orth, et al., 2013). This may be observed by examining how climbing actions differ through practice. For example, over repeated attempts, different route pathways, body orientations or grasping patterns might be used, reflecting exploration emerging during learning. Thus, during intervention the nature of learning behavior in so far that it can be related to the progression toward higher levels of performance (or fluency) may be better understood by evaluating the level at which exploration emerges.

A substantial challenge, in future research is in measuring exploration at different levels of analysis with respect to performance, both, in technically manageable and theoretically consistent ways (Orth et al., 2016; Schmidt, Orth, & Seifert, 2016). For instance, whilst, performatory and exploratory actions are predominantly assessed by considering overt action at the limbs, such characteristics are distinguishable across other levels, such as overall organization of the body (Russell et al., 2012; Seifert, Dovgalecs, et al., 2014), postural regulation (Boulanger, Seifert, Hérault, & Coeurjolly, 2016), visual search (Nieuwenhuys et al., 2008) and at more refined levels of control at hand-hold interaction (Fuss & Niegl, 2008) and are a clear research challenge for future work.

In particular the role of exploration for improving transfer is worth more attention. Indeed, any on-sight climb (where a climber attempts to climb a route they have never physically practiced) might be conceptualized as a skill transfer problem, requiring adaptations during performance with unfamiliar surface properties and in contexts with dynamic environments (such as outdoors). Assuming positive transfer (Carroll, Riek, & Carson, 2001; Issurin, 2013) is supported by the ability to skillfully search out efficient route pathways and climbing opportunities, interventions aiming to improve performance on new routes should consider the functional role of exploration during practice.

7. Conclusion

This review has demonstrated the importance of relating fluency and activity measures for understanding climbing actions and performance outcomes. Whilst numerous variables have been reported across the extant literature, many of these fail to capture how climbers adapt to a route whilst climbing. We have argued that there should be an emphasis on considering spatiotemporal measures concurrent with the evaluation of climbing specific activity states. Depending on the level of detail, such states can include: immobility; postural regulation; grasping; grip change; active recovery; reaching; reaching and withdrawing; traction; and, chaining movements in succession. In doing so, a more comprehensive picture of how climbers successfully adapt to a given route can be taken. In particular, the climbers intentions should be easier to estimate. For example, by combining these data, it is possible to more accurately determine if an individual is stopping in order to recover or because they cannot perceive opportunities for how to progress. We have also highlighted limitations in traditional performance measures (i.e., entropy and immobility). If activity analysis is not feasible, the main recommendation is that entropy and immobility should be concurrently assessed with respect to jerk. In doing so, the efficiency with which a climber is able to co-adapt movement complexity with required mobility can be addressed.

For future research, there is a major lack of understanding for how climbers transfer their skill to new routes and warrants more innovative approaches. Skill transfer is an essential part of climbing and indeed physical activity and sports in general. We anticipate that more successful climbers are more effective in how they explore new routes. Thus, characterizing how exploration is functional to climbers, and how they learn to explore effectively, such as based on practice constraints that require exploration, is a key problematic for future work.

8. References

Amca, A. M., Vigouroux, L., Aritan, S., & Berton, E. (2012). Effect of hold depth and grip technique on maximal finger forces in rock climbing. *Journal of Sports Sciences, 30*(7), 669-677.

Balagué, N., Hristovski, R., & Aragonés, D. (2012). Nonlinear model of attention focus during accumulated effort. *Psychology of Sport and Exercise, 13*(5), 591-597.

Billat, V., Palleja, P., Charlaix, T., Rizzardo, P., & Janel, N. (1995). Energy specificity of rock climbing and aerobic capacity in competitive sport rock climbers. *Journal of Sports Medicine and Physical Fitness, 35*(1), 20-24.

Boschker, M. S., & Bakker, F. C. (2002). Inexperienced sport climbers might perceive and utilize new opportunities for action by merely observing a model. *Perceptual and Motor Skills, 95*(1), 3-9.

Boschker, M. S., Bakker, F. C., & Michaels, C. F. (2002). Memory for the functional characteristics of climbing walls: Perceiving affordances. *Journal of Motor Behavior, 34*(1), 25-36.

Boulanger, J., Seifert, L., Dovgalecs, V., Herault, R., Orth, D., & Davids, K. (2014). *Automatic detection of climbing affordances.* Paper presented at the 4th International Conference on Complex Systems and Applications, France, Le Havre.

Boulanger, J., Seifert, L., Hérault, R., & Coeurjolly, J. F. (2015). Automatic sensor-based detection and classification of climbing activities. *Sensors Journal, IEEE*.

Boulanger, J., Seifert, L., Hérault, R., & Coeurjolly, J. F. (2016). Automatic sensor-based detection and classification of climbing activities. *Sensors Journal, IEEE, 16*(3), 742-749.

Carroll, T. J., Riek, S., & Carson, R. G. (2001). Neural adaptations to resistance training. *Sports Medicine, 31*(12), 829-840.

Cordier, P., Dietrich, G., & Pailhous, J. (1996). Harmonic analysis of a complex motor behavior. *Human Movement Science, 15*(6), 789-807.

Cordier, P., Mendès-France, M., Bolon, P., & Pailhous, J. (1993). Entropy, degrees of freedom, and free climbing: A thermodynamic study of a complex behavior based on trajectory analysis. *International Journal of Sport Psychology, 24*, 370-378.

Cordier, P., Mendès-France, M., Bolon, P., & Pailhous, J. (1994). Thermodynamic study of motor behaviour optimization. *Acta Biotheoretica, 42*(2-3), 187-201.

Cordier, P., Mendès-France, M., Pailhous, J., & Bolon, P. (1994). Entropy as a global variable of the learning process. *Human Movement Science, 13*(6), 745-763.

Davids, K., Araújo, D., Seifert, L., & Orth, D. (2015). Expert performance in sport: An ecological dynamics perspective In J. Baker & D. Farrow (Eds.), *Routledge Handbook of Sport Expertise* (pp. 130-144): Routledge.

Davids, K., Hristovski, R., Araújo, D., Serre, N. B., Button, C., & Passos, P. (Eds.). (2014). *Complex Systems in Sport*. London: Routledge.

Draper, N., Canalejo, J. C., Fryer, S., Dickson, T., Winter, D., Ellis, G., . . . North, C. (2011). Reporting climbing grades and grouping categories for rock climbing. *Isokinetics and Exercise Science, 19*(4), 273-280.

Draper, N., Dickson, T., Fryer, S., & Blackwell, G. (2011). Performance differences for intermediate rock climbers who successfully and unsuccessfully attempted an indoor sport climbing route. *International Journal of Performance Analysis in Sport, 11*(3), 450-463.

Elliott, D., Hansen, S., Grierson, L. E., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal-directed aiming: Two components but multiple processes. *Psychological bulletin, 136*(6), 1023.

Fryer, S., Dickson, T., Draper, N., Eltom, M., Stoner, L., & Blackwell, G. (2012). The effect of technique and ability on the VO2–heart rate relationship in rock climbing. *Sports Technology, 5*(3-4), 143-150.

Fuss, F. K., & Niegl, G. (2008). Instrumented climbing holds and performance analysis in sport climbing. *Sports Technology, 1*(6), 301-313.

Fuss, F. K., Weizman, Y., Burr, L., & Niegl, G. (2013). Assessment of grip difficulty of a smart climbing hold with increasing slope and decreasing depth. *Sports Technology, 6*(3), 122-129.

Green, A. L., Draper, N., & Helton, W. S. (2014). The impact of fear words in a secondary task on complex motor performance: A dual-task climbing study. *Psychological Research, 78*(4), 557-565.

Green, A. L., & Helton, W. S. (2011). Dual-task performance during a climbing traverse. *Experimental Brain Research, 215*, 307-313.

Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of Motor Behavior, 36*(2), 212-224.

Hardy, L., & Hutchinson, A. (2007). Effects of performance anxiety on effort and performance in rock climbing: A test of processing efficiency theory. *Anxiety, Stress, and Coping, 20*(2), 147-161.

Issurin, V. B. (2013). Training transfer: Scientific background and insights for practical application. *Sports Medicine, 43*(8), 675-694.

Laffaye, G., Collin, J. M., Levernier, G., & Padulo, J. (2014). Upper-limb power test in rock-climbing. *International Journal of Sports Medicine, 35*(8), 670-675.

Magiera, A., Roczniok, R., Maszczyk, A., Czuba, M., Kantyka, J., & Kurek, P. (2013). The structure of performance of a sport rock climber. *Journal of Human Kinetics, 36*(1), 107-117.

Nieuwenhuys, A., Pijpers, J. R., Oudejans, R. R., & Bakker, F. C. (2008). The influence of anxiety on visual attention in climbing. *Journal of Sport & Exercise Psychology, 30*(2), 171-185.

Orth, D., Button, C., Davids, K., & Seifert, L. (2017). What current research tells us about skill acquisition in climbing. In L. Seifert, P. Wolf, & A. Schweizer (Eds.), *The Science of Climbing and Mountaineering*: Routledge.

Orth, D., Davids, K., & Seifert, L. (2014). Hold design supports learning and transfer of climbing fluency. *Sports Technology, 7*(3-4), 159-165.

Orth, D., Davids, K., & Seifert, L. (2016). Coordination in climbing: effect of skill, practice and constraints manipulation. *Sports Medicine, 46*(2), 255-268.

Pezzulo, G., Barca, L., Bocconi, A. L., & Borghi, A. M. (2010). When affordances climb into your mind: Advantages of motor simulation in a memory task performed by novice and expert rock climbers. *Brain and Cognition, 73*(1), 68-73.

Pijpers, J. R., Oudejans, R. R., & Bakker, F. C. (2005). Anxiety-induced changes in movement behaviour during the execution of a complex whole-body task. *The Quarterly Journal of Experimental Psychology Section A, 58*(3), 421-445.

Pijpers, J. R., Oudejans, R. R., & Bakker, F. C. (2007). Changes in the perception of action possibilities while climbing to fatigue on a climbing wall. *Journal of Sports Sciences, 25*(1), 97-110.

Pijpers, J. R., Oudejans, R. R., Bakker, F. C., & Beek, P. J. (2006). The role of anxiety in perceiving and realizing affordances. *Ecological Psychology, 18*(3), 131-161.

Pijpers, J. R., Oudejans, R. R., Holsheimer, F., & Bakker, F. C. (2003). Anxiety–performance relationships in climbing: a process-oriented approach. *Psychology of Sport and Exercise, 4*(3), 283-304.

Rietveld, E., & Kiverstein, J. (2014). A rich landscape of affordances. *Ecological Psychology, 26*(4), 325-352.

Robert, T., Rouard, A., & Seifert, L. (2013). Biomechanical analysis of the strike motion in ice-climbing activity. *Computer methods in biomechanics and biomedical engineering, 16*(sup1), 90-92.

Russell, S. D., Zirker, C. A., & Blemker, S. S. (2012). Computer models offer new insights into the mechanics of rock climbing. *Sports Technology, 5*(3-4), 120-131.

Sanchez, X., Boschker, M. S. J., & Llewellyn, D. J. (2010). Pre-performance psychological states and performance in an elite climbing competition. *Scandinavian Journal of Medicine and Science in Sports, 20*(2), 356-363.

Sanchez, X., Lambert, P., Jones, G., & Llewellyn, D. J. (2012a). Efficacy of pre-ascent climbing route visual inspection in indoor sport climbing. *Scandinavian Journal of Medicine and Science in Sports, 22*(1), 67-72.

Sanchez, X., Lambert, P., Jones, G., & Llewellyn, D. J. (2012b). Efficacy of pre-ascent climbing route visual inspection in indoor sport climbing. *Scandinavian Journal of Medicine and Science in Sports, 22*, 67-72.

Schmidt, A., Orth, D., & Seifert, L. (2016). *Collection of visual data in climbing experiments for addressing the role of multi-modal exploration in motor learning efficiency*. Paper presented at the In International Conference on Advanced Concepts for Intelligent Vision Systems.

Seifert, L., Boulanger, J., Orth, D., & Davids, K. (2015). Environmental design shapes perceptual-motor exploration, learning, and transfer in climbing. *Frontiers in Psychology, 6*, 1819.

Seifert, L., Coeurjolly, J. F., Hérault, R., Wattebled, L., & Davids, K. (2013). Temporal dynamics of inter-limb coordination in ice climbing revealed through change-point analysis of the geodesic mean of circular data. *Journal of Applied Statistics, 40*(11), 2317-2331.

Seifert, L., Dovgalecs, V., Boulanger, J., Orth, D., Hérault, R., & Davids, K. (2014). Full-body movement pattern recognition in climbing. *Sports Technology, 7*(3-4), 166-173.

Seifert, L., Orth, D., Boulanger, J., Dovgalecs, V., Hérault, R., & Davids, K. (2014). Climbing skill and complexity of climbing wall design: Assessment of jerk as a novel indicator of performance fluency. *Journal of Applied Biomechanics, 30*(5), 619-625.

Seifert, L., Orth, D., Button, C., Brymer, E., & Davids, K. (2017). An ecological dynamics framework for the acquisition of perceptual–motor skills in climbing. In F. Feletti (Ed.), *Extreme Sports Medicine* (pp. 365-382): Springer International Publishing.

Seifert, L., Orth, D., Herault, R., & Davids, K. (2013). Affordances and grasping action variability during rock climbing In T. J. Davis, P. Passos, M. Dicks, & J. A. Weast-Knapp (Eds.), *Studies in Perception and Action: Seventeenth International Conference on Perception and Action* (pp. 114-118). New York: Psychology Press.

Seifert, L., Wattebled, L., Herault, R., Poizat, G., Adé, D., Gal-Petitfaux, N., & Davids, K. (2014). Neurobiological degeneracy and affordance perception support functional intra-individual variability of inter-limb coordination during ice climbing. *PloS one, 9*(2), e89865.

Seifert, L., Wattebled, L., L'Hermette, M., & Herault, R. (2011). Inter-limb coordination variability in ice climbers of different skill level. *Education, Physical Training and Sport, 1*(80), 63-68.

Seifert, L., Wattebled, L., L’Hermette, M., Bideault, G., Herault, R., & Davids, K. (2013). Skill transfer, affordances and dexterity in different climbing environments. *Human Movement Science, 32*(6), 1339-1352.

Sibella, F., Frosio, I., Schena, F., & Borghese, N. A. (2007). 3D analysis of the body center of mass in rock climbing. *Human Movement Science, 26*(6), 841-852.

Smyth, M. M., & Waller, A. (1998). Movement imagery in rock climbing: Patterns of interference from visual, spatial and kinaesthetic secondary tasks. *Applied Cognitive Psychology, 12*(2), 145-157.

Tosi, P., Ricci, L., Rosponi, A., & Schena, F. (2011). A theory of energy cost and speed of climbing. *AIP Advances, 1*(3), 032169.

Vigouroux, L., & Quaine, F. (2006). Fingertip force and electromyography of finger flexor muscles during a prolonged intermittent exercise in elite climbers and sedentary individuals. *Journal of Sports Sciences, 24*(2), 181-186.

Watts, P. B., Drum, S. N., Kilgas, M. A., & Phillips, K. C. (2016). Geometric entropy for lead vs top-rope rock climbing. *International Journal of Exercise Science, 9*(2), 168-174.

White, D. J., & Olsen, P. D. (2010). A time motion analysis of bouldering style competitive rock climbing. *The Journal of Strength & Conditioning Research, 24*(5), 1356-1360.

Zampagni, M. L., Brigadoi, S., Schena, F., Tosi, P., & Ivanenko, Y. P. (2011). Idiosyncratic control of the center of mass in expert climbers. *Scandinavian Journal of Medicine and Science in Sports, 21*(5), 688-699.

Figure Captions

Figure 1. Panel A: Exemplified is the shorter the path length within a given convex hull, the lower the geometric index of entropy (GIE). **Panel B:** The advanced climber (blue line) shows a more straight forward trajectory (and thus lower GIE) compared to the beginner (red line). **Panel C:** By the 42nd trial (blue line), the same individual does not show blocked periods, reducing the GIE. **Panel D:** An individual was asked to climb the same route either with the front of the body remained facing the wall (red line) or with the side of the body facing the wall (blue line). The more advanced technique required an increase in movement complexity. NB: All exemplary data are on the same route designed with French rating scale of difficulty = 5a. m = metres.

Figure 2. The relationship between entropy and immobility as a function of wall position. Note that radius of each point was scaled to increase in proportion to the duration spent in a given state (thus the larger the dot, the longer the individual was in the given state of mobility (i.e., blue line) or immobility (redline). c = convex hull. GIE = geometric index of entropy. IMR = immobility to mobility. m = metres.

Table 1. Studies fulfilling inclusion criteria.

Study[a]	Sample[b]	Design[c]	Task[d]	Measure[e]	Outcome[f]
	Spatial				
Boschker & Bakker (2002) [MMD] [Journal article]	N = 24,18-28 yrs, no experience: control subgroup (n = 8); dual grasping model subgroup (n = 7); arm-crossing technique model subgroup (n = 9)	A. Pedagogical intervention (model) i. control (observed the climbing wall) ii. simple technique model (observed an expert climber 4 times using a basic climbing technique) iii. advanced technique model (observed an expert climber 4 times using an advanced climbing technique) B. Practice (t x 5) [note: all observations were on a video, when observing the expert model, playback speed was first in slow motion (x2) and then normal (x2)]	Climb (indoor, artificial, top-roped, F-RSD = 5c [1, Intermediate], crux = 1,7 m height, 3.5 m width, 98.2 deg relative to floor, 22 holds) instructed to climb using the same technique as observed model otherwise self-preferred	Movement (hip trajectory, discrete actions) single camera: 1. GIE 2. falls [climb time]	At trial 2, 3 and 4, the advanced technique subgroup climbed significantly faster than the control and simple technique subgroup; at trial 1, 1 was significantly lower in the advanced technique subgroup compared to the simple technique subgroup and significantly lower in the control subgroup compared to the simple technique subgroup; at trials 2, 3 and 4, 1 was significantly lower in the advanced technique subgroup compared to the control and simple technique subgroups
Cordier, Mendès-France, et al.	N = 7: average skill subgroup (n = 3, F-	A. Skill B. Practice (t x 10)	Climb (indoor, artificial, top-	Movement (hip trajectory) single	1 was significantly lower in highly

(1993) [MMD] [Journal article]	RSD = 6b-6c [1.75-2.25, Intermediate]); highly skilled subgroup (n = 4, F-RSD = 7a-7b [2.5-3, Intermediate-, Advanced])		roped, F-RSD = 6a [1.25, Intermediate], ~10 m high) self-preferred	camera: 1. GIE 2. fractal dimensions [climb time]	skilled subgroup; 1 significantly decreased with practice in both groups; [note: a significant interaction effect between skill and practice showed that 1 reduced faster in the higher skilled subgroup compared to the lesser skilled subgroup; a clear correlation was shown between climb time and entropy with higher climb times being associated with higher entropy]
Cordier, Mendès-France, et al. (1994) [MMD] [Journal article]	Average skill subgroup (F-RSD = 6b [1.75, Intermediate]); highly skilled subgroup (F-RSD = 7b [3, Advanced]) [note: the exact number of individuals making up each sub-group not reported]	A. Skill B. Practice (t x 10)	See above, Cordier, Mendès-France, et al. (1993)	Movement (hip trajectory) single camera: 1. GIE [climb time]	Highly skilled subgroup showed less 1 compared to the average skilled subgroup; with practice 1 significantly reduced; highly skilled subgroup reduced entropy faster with practice than the skilled group;

					[note: highly skilled subgroup reduced entropy to asymptote by trial three whereas the average skill subgroup did not reach a clear asymptote after 10 trials of practice]
Cordier, Mendès-France, Pailhous, et al. (1994) [MMD] [Journal article]	N = 10: non-expert subgroup (n = 5, F-RSD = 6b [1.75, Intermediate]); expert subgroup (n = 5, F-RSD = 7b [3, Advanced])	A. Skill B. Practice (t x 10)	See above, Cordier, Mendès-France, et al. (1993)	Movement (hip trajectory) single camera: 1. GIE [climb time]	Highly skilled subgroups showed overall less entropy compared to the average skilled subgroup; With practice entropy significantly reduced; Highly skilled group reduced entropy faster with practice than the average skilled group; Highly skilled group reduced entropy to asymptote by trial three. Unskilled group did not appear to reach asymptote.
Pijpers, Oudejans,	N = 17, 11 M, 19-26	A. Route design	Climb (indoor,	Movement (hip	1 and climb time

et al. (2003) [RM] [Journal article] – Experiment 2	yrs, little to no experience in climbing	(height) i. mean height of foot holds 0.3 m from the ground ii. foot holds 3.7 m from the ground	artificial, top-rope, flush vertical, 6 hand- and 5 foot-holds, 7 m height, 3.5 m width) nr [note: difficulty assumed as easily achievable; participants practiced on route before testing; each trial required 20 sec continuous climbing]	trajectory) single camera: 1. GIE [climb time, HR and state anxiety]	significantly increased when climbing in the high condition.
Sanchez, Boschker, et al. (2010) [IG] [Journal article]	N = 19, 24.6 yrs±4.0SD, elite climbers, F-RSD = 7b+ to 8b [3.25-4.5, Advanced-Elite]: successful subgroup (n = 9); unsuccessful subgroup (n = 7) [note: successful subgroup membership criteria required that the climbers get to at least the 39th hold (out of 50). Those who did not were assigned to the unsuccessful	A. Skill	Climb (artificial, F-RSD = 7c+ [3.75, Advanced]], crux = 2, rest points = 2, on-sight, 16 m high, 50 handholds) competition [preview = 5 mins]	Movement (hip trajectory) single camera: 1. GIE (section 1 crux, section 1, section 2) 2. climb time (section 1 crux, section 1, section 2) [precompetitive state anxiety] [note: 16/19 of the climbers were analyzed; for analysis the route was broken into 2 sections and 2 crux points]	2 was significantly longer in the successful subgroup compared to the unsuccessful subgroup in the first crux.

	subgroup.]				
Zampagni, Brigadoi, et al. (2011) [IG] [Journal article]	N = 18 M: elite subgroup (n = 9, 32.1 yrs±7.6SD, F-RSD = 7b-8b [3-4.5, Advanced-Elite], climbing age = 13.9 yrs); no experience subgroup (n = 9, 31.9 yrs±8.5SD)	A. Skill	Climbing (artificial, top-rope, 20 holds, uniform holds = 13 cm high, 16 cm wide, 12 cm deep) under instruction [note: instructed on the sequence of which limb to reposition and to which hold, this pattern was repeated until climbers reached the top; climbers were required to complete each cycle within 4 seconds]	Movement, applied force (COM, hands and feet) mulit-camera, instrumented holds: 1. COM anterior/posterior and lateral motion (min, mean, max) 2. force (vertical component)	The expert subgroup climbed with 1 significantly further from the wall and with larger lateral displacements compared to the no experience subgroup; 2 showed significantly larger oscillations in the expert subgroup compared to the no experience subgroup.
	Temporal				
Billat, Palleja, et al. (1995) [RM] [journal article]	N = 4, 22.2 yrs±2.3SD, F-RSD = 7b [3, Advanced], climbing age = 3 yrs	A. Hold (size) & Wall (slope) i. smaller more complex hold design ii. steeper slope [note: difficulty matched]	Climb (indoor, artificial, F-RSD = 7b [3, Advanced], red-point, 15 m high, ~10 deg overhang) self-preferred [note: 5 hrs	Movement (discrete actions) single camera: 1. Dynamic time (discernable motion at the hips) 2. Static time (no discernable motion at the hips)	1 was significantly longer on the smaller more complex route compared to the route with a larger overhang.

			practice on each route prior to testing]	[note: additional variables of interest related to oxygen consumption]	
Cordier, Mendès-France, et al. (1996) [MMD] [Journal article]	N = 10: non-expert subgroup (n = 5, F-RSD = <7a [<2.5, Intermediate]); expert subgroup (n = 5, F-RSD > 7a [>2.5, Advanced])	A. Skill B. Practice (t x 10)	See above, Cordier, Mendès-France, et al. (1993)	Movement (hip trajectory) single camera: 1. Frequency of movement (Hz) 2. Harmonic analysis	Expert subgroup generated approximately one movement every three seconds and were closer to the harmonic model by a factor of about two compared to the non-expert subgroup.
Draper, Dickson, et al. (2011) [MMD] [Journal article]	N = 18, 12 M, 25.6±4.5 intermediate level, onsight lead F-RSD = 5+ [1, Intermediate], red-point F-RSD = 6a [1.25, Intermediate] climbing age 3.6yrs±3.1	A. Route Type i. tope-rope ii. lead rope B. Route completion i. yes (n = 11) ii. no (n = 7) [note: group formed post hoc based on those who did or did not fall]	Climb (indoor, artificial, F-RSD = 6a, 12.5 m height, 7 quick-draws) self-preferred	Movement (climb time) single-camera [yrs experience, NASA-TLX, CSAI-2D, oxygen consumption, blood lactate, HR] 1. Climb time (between successive quick-draws)	Experience was the best predictor of climbing success and was also correlated with confidence and faster climbing within challenging parts of an ascent. Climbers that fell were slower through the route
White & Olsen (2010) [Journal article] [RM]	N = 6, elite, age = 28yrs±5SD, climbing age = 16yrs±5SD	Observational	Climb (indoor, artificial, bouldering) competition	Movement (discrete actions) two-cameras: 1. hand contact time	A larger proportion of time is spent in dynamic movement relative to static.

	[note: sample argued elite, held an IFSC World ranking for the World Cup boulder series and members of British national team]		[a total of 12 climbs were recorded, two climbs per individual, each on a different route]	2. reach time 3. dynamic time 4. static time [number of attempts, climb time, total attempt time, between attempt recovery time]	Hand contact time was larger than reach time.
	Activity analysis				
Nieuwenhuys, Pijpers, et al. (2008) [RM] [Journal article]	N = 12, 7 M, 24.4 yrs±1.98SD, no experience	A. Route design (height) i. holds 0.44 m from the ground ii. holds 4.25 m from the ground	Climb (indoor, artificial, top-rope, 26 hand- and foot-holds) self-preferred [note: difficulty level assumed to be easily achievable; participants practiced on the route prior to testing]	Visual behavior, movement (gaze-location, discrete actions) eye-tracker, single camera; 1. fixation (duration, number, average duration, duration per location, duration per type, search rate) [note: possible fixation locations included handholds, hands, wall, other and possible fixation types were exploratory or performatory] 2. mean distance of fixation 3. movement time (climb time,	Climb time, movement time between holds and time spent static was significantly longer and number of movements were significantly greater in the high condition compared to the low condition; Fixation durations were significantly longer, number of fixations significantly increased, and search rate significantly decreased in the high condition compared to the low condition.

				stationary time, moving time (hands and feet), average movement duration between holds) 4. mean distance of hand movements [nb: additional measures of interest were HR and anxiety]	
Pijpers, Oudejans, et al. (2005) [RM] [Journal article] – Experiment 1	N = 8 M, 31.4 yrs±4.81SD, no experience	A. Route design (height) i. mean height of foot holds 0.4 m from the ground ii. foot holds 5.0 m from the ground	Climb (indoor, artificial, top-rope, flush vertical, flash, 7 m height, 3.5 m width, 7 hand- and 6 foot-holds, mean inter-hold distance = 0.15 m) as fast and as safely as possible without falling: [note: difficulty not given but assumed to be easily achievable; participants practiced on low traverse prior to testing and observed an expert model perform the	Movement (discrete actions) multi-camera: 1. number of exploratory movements (number of times a hold is touched without use as support) 2. number of performatory movements 3. Use of additional holds (two holds not needed to achieve traversal were set into the route) [climb time, HR and anxiety data]	1 and climb time was significantly higher in the high condition compared to the low condition.

			traverse on video; each trial required 2 traversals]		
Pijpers, Oudejans, et al. (2006) [RM] [Journal article] – Experiment 2	N = 12, 6 F, 20.8 yrs±3.57SD, no experience	A. Route design (height) i. holds on average 0.36 m from the ground (t x 4) ii. holds 3.69 m from the ground (t x 4)	Climb (indoor, artificial, top-rope, flush vertical, 7 m height, 3.5 m width, 15 hand- and 15 foot-holds) as fast and as safely as possible without falling [note: difficulty not rated but assumed to be easily achievable; participants practiced on route before testing; each trial required 2 traversals]	Movement (discrete actions) single camera: 1. number of performatory actions (hands and feet) 2. number of exploratory actions (hands and feet) [climb time, state anxiety]	1, 2 and climb time increased significantly when climbing at height compared to close to the ground.
	Crossed				
Fryer, Dickson, et al. (2012) [IG] [Journal article]	N = 22: intermediate subgroup (n = 11, 7 M, F-RSD = 6a/ Ewbank = 18/19 [1.25, Intermediate], climbing age = 3±1.15yrs); advanced subgroup (n = 11, 10 M, F-RSD = 6c+/	A. Skill	Climb (indoor, artificial, top-roped, F-RSD = 6a [1.25, Intermediate] & 6c+ [2.25, Intermediate], on-sight, 12.15 m high, overhang) self-preferred	Movement (discrete actions) single camera: 1. time spent static (no hip motion) 2. time spent actively resting (shaking the limbs) [note: additional variables of interest	Advanced subgroup spent significantly greater proportion of their climb time in static states and more of the static time actively resting compared to the intermediate subgroup; [note:

	Ewbank = 21/22 [2.25, Advanced], climbing age = 3.3±1.06yrs)		[preview = 5 min] [note: difficulty matched to subgroup skill levels]	related to HR, mood state, anxiety]	significantly lower heart rates in the advanced subgroup compared to the intermediate subgroup are interpreted as related to the time spent in active recovery]
Pijpers, Oudejans, et al. (2005) [RM] [Journal article] – Experiment 2	N = 15, 13 M, 20.7±2.22SD yrs, no experience	A. Route design (height) i. mean height of foot holds 0.4 m from the ground ii. foot holds 4.9 m from the ground	Climb (indoor, artificial, top-rope, flush vertical, 7 m height, 3.5 m width, 6 hand- and 5 foot-holds) as fast and as safely as possible without falling: [note: difficulty not given but assumed to be easily achievable; participants practiced on low traverse prior to testing and observed an expert model perform the traverse on video; each trial; 4 traversals	Movement (discrete actions) mulit-camera, instrumented holds: 1. number of explorative movements 2. number of performatory movements (hands and feet) 3. rest between traversals 4. contact time (total, hands, feet, average per hold, total and for feet and hands) [climb time, HR, anxiety]	1 and 2 (feet only) was significantly greater and 4 (total, feet and hands, average total and average feet) was significantly longer in the high condition compared to the low condition. [note: climb time was significantly longer in the high condition compared to the low condition]

			required per condition]		
Sanchez, Lambert, et al. (2012b) [MMD] [Journal article]	N = 29: intermediate subgroup, (n = 9, F-RSD = 6a – 6b [1.25-1.75, Intermediate]); advanced subgroup, (n = 9, F-RSD = 7a-7a+ [2.5-2.75, Intermediate-Advanced]), expert subgroup, (n = 11, F-RSD > 7b+ [>3.25, Advanced])	A. Skill B. Preview: i. with preview (3 min) ii. without preview	Climb (indoor, top-rope, on-sight) self-preferred [preview = 3 minutes (when given)] [note: a total of 6 routes were involved, route difficulties as follows: i. 2 intermediate routes (6a [1.25, Intermediate], 6a+[1.5, Intermediate]) ii. 2 advanced routes (both 6c [2.25, Intermediate]) iii. 2 expert routes (7b, 7c [3.5, Advanced]); participants only climbed routes that were either equal to or less than their F-RSD level]	Movement (discrete actions) single camera: 1. number of movements (performatory & exploratory) 2. duration of movements (performatory & exploratory) 3. number of stops (appropriate & inappropriate) 4. duration of stops (appropriate & inappropriate)	3 (appropriate) and 4 (appropriate) were significantly longer when climbing without preview in the expert subgroups compared to the intermediate and advanced subgroups on the route matched to skill level.
Seifert, Coeurjolly,	N = 15 M: expert	A. Skill	Climb (outdoors,	Movement (upper	1 showed a 1:1 ratio

et al. (2013) [IG] [Journal article]	subgroup (n = 7, 32.1 yrs±4.0SD, F-RSD = 7a+ to 7c [2.75-3.5, Advanced], F-RSD for ice falls = 6-7, rock-climbing age = 17.1, ice climbing age = 10.4 yrs); beginner subgroup (n = 8, 28.5 yrs±6.4SD, climbing age ~ 20 hrs practice on artificial walls, no experience in ice climbing)		ice fall, 85 deg ramp, 30 m high, top-rope) self-preferred [note: Route difficulty: i. grade 5+ (F-RSD for ice-falls) i. grade 4 (F-RSD for ice-falls); participants only climbed routes that were equal to their F-RSD level]	and lower body) single camera: 1. exploration index (ratio of ice tool swings to definitive anchorages for upper and lower limbs) 2. relative angular position (upper and lower limbs pairs relative to the horizontal)	in the expert subgroup for both the upper and lower limbs whereas 1 showed a ratio of 0.6 and 0.2 in the upper and lower limbs respectively in the beginner subgroup (i.e. more non performatory movements); 2 showed more variability in the relative angular positions in the expert subgroup compared to the novice subgroup.
Seifert, Orth, et al. (2014) [Journal article]	N = 8, 21.4yrs±2.4SD, top-rope, F-RSD = 6a [2, Intermediate], climbing age = 4.1yrs±2.1SD	A. Route design (holds) i. single edged (all edges parallel to ground) ii. double edged (one edge parallel to ground, one edge perpendicular to ground) B. Practice (4 trials)	Climb (indoors, artificial, top-roped, on-sight & practice, F-RSD = 5c [1, Intermediate] 10 m height, 20 holds, preview = 3 mins) self-preferred [note: each hold had two graspable edges]	Movement (hip) worn sensor 1. jerk coefficient (normalized) [note: rotation and position analysis] 2. Exploratory movements	1 was higher on double edged (more complex) route. 1 decreased with practice. 2 decreased with practice. [note: of additional interest was the strong correlation between rotational and positional coefficients of jerk]
Seifert, Wattebled, et al. (2013) [IG]	N = 15, 24.5 yrs±4.5SD, naïve	A. Skill [note: research	Climb (outdoors, ice, 30 m high,	Movement (discrete actions) single	1 was closer to a ratio of one swing

[Journal article]	ice climbers: novice subgroup (n = 10, F-RSD < 5 [<0.75, Lower grade], climbing age = 10 hrs practice on artificial walls); intermediate subgroup (n = 5, F-RSD = 6a [<1.25, Intermediate], climbing age = 3 yrs)	question of interest was whether skill influenced transfer to different environmental properties based on the climbers history. IV corresponds to: B. Transfer i. rock climbing; ii. ice climbing.]	top-rope, route F-RSD for ice falls = 4) self-preferred	camera: 1. exploration index (ratio of ice tool swings to definitive anchorages for upper and lower limbs) 2. relative angular position (upper and lower limbs pairs relative to the horizontal) 3. relative phase (upper and lower limb pairs) [note: see note in Seifert, Wattebled, et al., (2011)] 4. vertical distance climbed in 5 mins 5. plateau duration (plateau defined as less than 0.15 m of vertical displacement for longer than 5 s)	to one definitive anchorage for intermediate subgroup compared to the novice subgroup; 2 and 3 showed significantly greater variability in the intermediate subgroup compared to the novice subgroup; 4 was significantly greater and 5 was significantly shorter in the intermediate subgroup compared to the novice subgroup. [note: of additional interest in this study was to undertake an unsupervised hierarchical cluster analysis using the DVs to classify the climbers into different skill based subgroups.
Seifert, Wattebled, et al. (2014) [IG] [Journal article]	N = 14; expert climber subgroup (n = 7, 32.1±6.1SD, F-RSD for rock = 7a+-	A. Skill	Climb (outdoors, ice, top-rope; 30 m high) self-preferred	Movement, verbalization (discrete actions, self-confrontation	Expert subgroup achieved greater vertical displacement, had

	7c [2.75-3.5, Intermediate], F-RSD for icefalls = 6-7, climbing age = 17.4yrs±5.6); beginner subgroup (n = 7, 29.4 yrs±6.8, climbing age = <20hrs indoor climbing practice)		[note: a total of 2 routes were involved, the expert subgroup were tested on a grade 5+ (F-RSD for ice-falls); the beginner subgroup were tested on a grade 4 (F-RSD for ice-falls)]	interview) single camera, audio: 1. number & duration of stops 2. relative angular position (upper and lower limbs pairs relative to the horizontal) 3. exploratory & performatory actions 4. Verbalisations i. perceptions ii. actions iii. intentions	more stoppages but that were shorter in duration, explored a larger angular range with ice-tools, less exploratory actions compared to beginner subgroup. Expert subgroup verbalized about information related to behavioral opportunities that were multi-modal and intentions were focused on vertical traversal. Beginners focused on visual cues for putting their ice-hooks into the wall and focused intentions on remaining on the wall.
Sibella, Frosio, et al. (2007) [RM] [Journal article]	N = 12, 30.6 yrs16-49, recreational, non-competitive climbers, training 1-2 x per week: agility style climber subgroup (n = 1); force style climber subgroup (n = 1)	A. Skill [note: skill groups formed post-hoc, by identifying different climbing strategies using kinematic measures]	Climb (indoor, artificial, top-rope, F-RSD = 4b [0.25, Lower grade], 3 m traverse, 3 m ascent) self-preferred [note: t x 5, data averaged across	Movement (COM) multi-camera: 1. GIE [note: computed for frontal, sagittal and transverse planes] 2. absolute velocity (COM) 3. absolute acceleration (COM)	1 was significantly lower (frontal and sagittal planes), 3 and 4 was significantly lower, and 5 was significantly higher in the agility style climber compared to the force style

			participants]	4. power of acceleration time course (COM) 5. mean number of holds in contact per recorded frame of video (60 hz)	climber; 2 was significantly lower in the agility style climber compared to the entire group of climbers and 2 was significantly higher in the force style climber compared to the entire group of climbers.

a, author (date) [experimental design] publication type
b, sample size; (sample characteristics: age, variability, climbing age, reported ability level [ability level converted to Watts]); subgroups.
c, Independent variable: A, B; level: i, …, iii.
d, Task: climb; (route properties: location (indoors; outdoors), wall properties (artificial; rock; ice, height, slope), type (top-rope; lead), route difficulty [Watts conversion (see [b])] ; instructions; [preview time]
e, Dependent variable type; (level or nature of analysis); measurement device; dependent variable 1, …, 5 (description and sub-levels) [additional variables]
f, variable(s) reported showing significant effect: 1, … , 5 (description of direction of effect and reported interpretation as position or negative for performance)

COF = coefficient of friction; COP = centre of pressure; CPEI = climbing performance evaluation inventory; CRP = continuous relative phase; Crux = a part of a route more difficult than others; deg = degrees; DV = dependent variable; F = female; flash = individuals have had a chance to observe another climber on the route prior to making an attempt; F-RSD = french rating scale of difficulty; IG = Independent groups; IV = independent variable; GIE = geometric index of entropy; HR = heart rate; hrs = hours; Hz = cycles per second; M = male; m = metres; max = maximum; min = minimum; mins = minutes; MMD = mixed methods design; NASA-TLX = National Aeronautics and Space Administration Task Load Index; nr = not reported; on-sight = the first attempt of a climbing route; PCA = Principle component analysis; red point = refers to performance on a route that has been previously practiced; s = seconds; SD = standard deviation; t = trials; UIAA = Union Internationale des Associations d'Alpinisme; vs. = versus; yrs = years.

Table 2. Relationships between spatiotemporal outcomes, discrete actions and climbers intentions.

Activity state	Limb activity (A) combined with spatial (GIE) and temporal (IMR) outcomes	Function (individual intentions)
Immobility	A: All limbs stationary and: 1. IMR ↑ and GIE ↓	1. Passive recovery (Seifert, Wattebled, et al., 2013); Visually explore (Nieuwenhuys et al., 2008; Sanchez et al., 2012a); establish base of support.
Active recovery	A: 1 limb moving and behind the body: 1. IMR ↑ and GIE ↓	1. Relieve the forearms, apply chalk (Fryer et al., 2012); Visually explore (Sanchez et al., 2012a)
Postural regulation	A: All limbs stationary and: 1. IMR ↓ and GIE ↑ 2. IMR ↓ and GIE ↓	1. Exploration of different body orientation(s) (Cordier et al., 1996; Cordier et al., 1993; Seifert et al., 2015). 2. Use of different body orientation(s).
Grasping	A: 1 limb moving and: 1. IMR ↑ and GIE ↓	1. Preparation for hold use (Boulanger, Seifert, Hérault, & Coeurjolly, 2015; Fuss & Niegl, 2008).
Grip change	A: 1 limb moving and: 1. IMR ↑ and GIE ↑	1. Explore hold grasp technique (Boulanger et al., 2015).
Reaching	A: 1 limb moving and: 1. IMR ↑ and GIE ↓	1. Change holds.
Reach and withdraw**	A: 1 limb moving and: 1. IMR ↑ and GIE ↓ 2. IMR ↑ and GIE ↑	1. Efficient exploratory reach (Seifert et al., 2015). 2. Inefficient exploratory reach (Seifert et al., 2015).

Traction	A: ≥1 limb moving and: 1. IMR ↑ and GIE ↓ 2. IMR ↓ and GIE ↑	1. Movement using face-on body position (Fuss et al., 2013). 2. Movement with body roll (Fuss et al., 2013).
Chaining movements in succession	A: ≥1 limb moving and: 1. IMR ↓ and GIE ↓	1. Fluent performance (Cordier et al., 1996).

IMR ↑ = means the individuals is more immobile; IMR = ↓ means the individual is more mobile; GIE ↓ = means the movement is less complex ; GIE ↑ = means the movement is more complex. ** Requires that the next state is not a lifting state, see Boulanger et al., (2014).