

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

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1 A review of relationships between spatiotemporal movement regulation and discrete actions for
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3 Activity states and performance during climbing

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5 **Author List:** Dominic Orth^{1,2}, Graham Kerr^{2,3}, Keith Davids⁴, Ludovic Seifert¹

6 **Affiliations:**

7 ¹ CETAPS - EA 3832, Faculty of Sport Sciences, University of Rouen, France.

8 ² School of Exercise and Nutrition Science, Queensland University of Technology, Brisbane, Australia.

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

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

12 **Corresponding author:**

13 Ludovic SEIFERT CETAPS EA3832 Faculty of Sports Sciences, University of Rouen Normandy Boulevard Siegfried
14 76821 Mont Saint Aignan cedex, France E-mail: ludovic.seifert@univ-rouen.fr Tel: (+33) 235 146 784 Fax: (+33)
15 235 147 793

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23

24 **Abstract**

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

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

50

51 **1. Introduction**

52 Traditionally, skilled climbing is characterized by the efficiency of spatial and temporal
53 patterns that emerge at the centre of mass (COM) during the act of climbing (Billat, Palleja,
54 Charlaix, Rizzardo, & Janel, 1995; Cordier, Dietrich, & Pailhous, 1996). Temporal assessment
55 quantifies the number and nature of stoppages relative to continuous climbing, indicating the
56 amount of time spent in isometric contraction (Billat et al., 1995; White & Olsen, 2010). Spatial
57 indicators highlight the efficiency of a climber's trajectory across the surface, estimating the
58 ability to perceive an efficient 'pathway' through the route (Boschker & Bakker, 2002; Cordier,
59 Mendès-France, Bolon, & Pailhous, 1993). Finally, combined spatiotemporal measures, such as
60 the minimization of jerk, globally indicate how smoothly climbing movements are linked
61 together (Seifert, Orth, et al., 2014). Importantly, evaluating performance along spatial and
62 temporal variables can address different mechanisms underpinning skilled climbing (Cordier et
63 al., 1996). For example, initial and rapid improvement in performance is believed to be primarily
64 influenced by the rapidly adapting visual-motor system (Pezzulo, Barca, Bocconi, & Borghi,
65 2010). Alternatively, a climber may improve performance by linking movements in a more
66 periodic fashion. These sorts of improvement occur over longer time-scales, such as the months
67 and years required for musculoskeletal system adaptation (Vigouroux & Quaine, 2006).

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

84 A limitation in the extant literature is that how an individual's specific activity state can
85 influence climbing efficiency is poorly understood, and, being able to combine these measures
86 can be tremendously informative (Orth, Davids, & Seifert, 2016). Indeed, approaches that have
87 considered these variables in combination have uncovered important insights into the functional
88 or goal-supportive characteristics of movement variability (Fryer et al., 2012; Seifert, Boulanger,
89 Orth, & Davids, 2015). For instance, Pijpers et al. (2006) implied that exploratory behavior
90 reflects poor performance. Whereas, more recent studies have combined the analysis of
91 exploratory actions with spatiotemporal performance outcomes, revealing that exploratory
92 actions can be related to an improvement in performance through practice (Seifert et al., 2015).
93 Thus, this review draws together studies that have reported on performance and discrete limb
94 actions in climbing tasks to evaluate how, in combination, these can explain successful and
95 efficient climbing. The review is structured into three parts. First, we examine the existing state

96 of the art on how spatial and temporal outcomes are used to quantify skilled climbing. Next, data
97 pertaining to activity states are considered with respect to their functionality for the individual.
98 Finally, hypotheses are presented for how activity states combined with spatial-temporal
99 outcomes can indicate specific intentions of climbers during the act of climbing.

100 **2. Search methodology**

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

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

133 **3. Results**

134 Using the search methodology, the Medline database yielded 1099 titles and abstracts. These
135 were screened yielding 35 relevant articles, which were identified and their full texts retrieved.
136 Relevant studies were then screened using the standardized inclusion criteria and 13 eligible
137 studies identified. Using the same search methodology, the SPORTDiscuss database was
138 searched. This yielded 2201 results, these titles and abstracts were screened, from which 59
139 relevant articles were identified. After duplicate removal, full texts were retrieved and eligibility

140 was assessed using the standardized inclusion criteria, identifying 15 studies this way. The related
141 articles, citing articles and reference lists of 7400 eligible studies were searched using Google
142 Scholar. 94 relevant studies were subsequently identified for eligibility screening. After
143 duplicates were removed, an additional 13 eligible studies were identified this way. The article
144 search was stopped at this point. From this pool of 41 studies, 22 fulfilled the eligibility criteria.
145 These are summarised to Table 1 and discussed below.

146 >>>Table 1 here<<<<

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

148 Data on skilled climbing behavior can reflect coordination of actions to route properties,
149 providing insights on the quality of movement adaptations. A number of studies have
150 incorporated spatial and temporal measures into a single outcome to quantify climbing fluency.
151 These have generally involved the analyses of the climbers' COM projection, to estimate velocity
152 (Cordier et al., 1996; Sibella, Frosio, Schena, & Borghese, 2007), acceleration (Cordier et al.,
153 1996; Sibella et al., 2007), jerk (Seifert, Orth, et al., 2014), and phase portrait patterning (Cordier
154 et al., 1996). Among these, being very much linked to the number sub-movements used in
155 carrying out an action (Elliott et al., 2010), jerk coefficients on hip movements provides the most
156 straightforward indication of capacity to co-adapt spatial-temporal demands of performance
157 (Seifert, Orth, et al., 2014). For example, Seifert et al. (2014) calculated jerk coefficients on three
158 dimensional hip translation and rotation accelerations. Here, jerk coefficients improved with
159 practice on a route that involved use of different types of grasping techniques (overhand grasping
160 and pinch grips), compared to no significant change on a route that required use of a single type
161 of action (overhand grasping) (Seifert, Orth, et al., 2014).

162 Whilst expertise in climbing involves highly adaptive and proficient performance along
163 both spatial and temporal dimensions in combination, current understanding of skill and practice
164 effects has been primarily approached by considering each dimension separately (Cordier et al.,
165 1996; Sibella et al., 2007).

166 **4.1 Spatial indicators of climbing fluency**

167 Spatial indicators relate to analyses of displacement on a surface. Existing approaches
168 include computation of the geometric index of entropy (GIE, see equation 1 below) (Boschker &
169 Bakker, 2002; Cordier et al., 1993; Cordier, Mendès-France, Bolon, & Pailhous, 1994; Cordier,
170 Mendès-France, Pailhous, & Bolon, 1994; Orth, Button, Davids, & Seifert, 2017; Pijpers,
171 Oudejans, Holsheimer, & Bakker, 2003; Sanchez, Boschker, & Llewellyn, 2010; Seifert et al.,
172 2015; Sibella et al., 2007; Watts, Drum, Kilgas, & Phillips, 2016), climb distance (Green, Draper,
173 & Helton, 2014; Green & Helton, 2011; Seifert, Wattebled, et al., 2014; Seifert, Wattebled, et al.,
174 2013), average movement distance (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008), COM-to-
175 wall distance (Zampagni, Brigadoi, Schena, Tosi, & Ivanenko, 2011), and planar displacement of
176 the COM (Zampagni et al., 2011). Interpreting the quality of displacement with respect to a route
177 is the main reason GIE has enjoyed widespread application (Boschker & Bakker, 2002; Cordier
178 et al., 1993; Cordier, Mendès-France, Bolon, et al., 1994; Cordier, Mendès-France, Pailhous, et
179 al., 1994; Pijpers et al., 2003; Sanchez et al., 2010; Seifert, Orth, Button, Brymer, & Davids,
180 2017; Sibella et al., 2007).

181 Specifically, GIE is given for a given trajectory $x : [0, T] \rightarrow R^3$, letting Δx be the
182 trajectory length (Equation 1) and $\Delta c(x)$ the convex hull parameter. The GIE is given by:

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

183 Equation 1

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

184 Equation 2

185 According to Cordier et al. (1994) the GIE can assess the amount of fluency of a curve.
 186 The higher the entropy value, the higher the irregularity of the climbing trajectory, whereas the
 187 lower the entropy value, the more regular is the climbed trajectory. GIE has a number of
 188 advantages over reported spatial variables, such as the average movement distance (Nieuwenhuys
 189 et al., 2008), in that it is based on theoretically generalizable principles (Cordier, Mendès-France,
 190 Pailhous, et al., 1994), readily interpreted with respect to climbing activity, and, is effective for
 191 detecting skill (Cordier et al., 1993), practice (Cordier et al., 1993), route (Seifert et al., 2017) and
 192 technique effects (Boschker & Bakker, 2002; Sibella et al., 2007). Furthermore, data collection to
 193 perform an entropy calculation is highly feasible involving use of a single camera (Sanchez et al.,
 194 2010). Figure 1 shows how entropy is calculated (Panel A) and with respect to how changing the
 195 length of an analysed trajectory with the convex hull affects outcomes.

196 In climbing tasks, entropy outcomes are particularly increased when route difficulty is
 197 hard relative to the ability level of the climber, sometimes referred to as functional task difficulty
 198 (Guadagnoli & Lee, 2004), and, the route has not yet been physically practiced (Cordier,
 199 Mendès-France, Pailhous, et al., 1994). For example, when the functional difficulty of a route is
 200 increased, by modifying the number of choices embedded into it, entropy increases even in
 201 experienced climbers (Seifert et al., 2015). Practice effects have also been reported, with
 202 performance after repeated practice generally converging to an asymptote level at a rate
 203 dependent on the initial skill level of the climbers. Typically, the higher the initial skill level, the
 204 more rapid an asymptote is reached (Cordier et al., 1993; Cordier, Mendès-France, Bolon, et al.,
 205 1994; Cordier, Mendès-France, Pailhous, et al., 1994). Intriguingly, Boschker and Bakker (2002)
 206 found that prior knowledge about advanced inter-limb coordination patterns can improve entropy
 207 in beginners, allowing them to improve performance faster through practice, see also (Seifert,
 208 Coeurjolly, Hérault, Wattedled, & Davids, 2013).

209 Notably in Boschker and Bakker (2002), practice of less advanced techniques also
 210 resulted in entropy values similar to those when advanced actions were used, suggesting that the
 211 route designs may not have required more advanced technique for improved performance.
 212 Sanchez et al. (2010) also raised the concern, that, when elite climbers were compared on routes
 213 close to the limits of their ability level, no relationship between the climbers' performance GIE
 214 was shown. This may have been because the climbers had not practised physically on the wall
 215 before testing began, and, the difficulty was close to the climbers' ability limit (Sanchez et al.,
 216 2010, p. 360). Implications of these studies suggest that, through observing repeated practice,
 217 larger learning effects can be expected when route difficulty is closer to a climber's ability level
 218 (Cordier et al., 1993). It is worth emphasizing, however, that these findings also indicate that in
 219 some cases a higher entropy may not necessarily indicate poor performance (Davids et al., 2014).

220 >>Figure 1 about here<<

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

236 **4.2 Temporal indicators of fluency**

237 Temporal measures interpreted with respect to continuity of climbing performance
238 include the: (i) relationship between static and dynamic movements at the hips (Billat et al., 1995;
239 Cordier, Mendès-France, Bolon, et al., 1994; Nieuwenhuys et al., 2008; Seifert, Wattedled, et al.,
240 2014; Seifert, Wattedled, et al., 2013; White & Olsen, 2010); (ii) relationship between hold
241 grasping and moving between holds (Nieuwenhuys et al., 2008; Pijpers, Oudejans, & Bakker,
242 2005; Pijpers et al., 2006; White & Olsen, 2010); (iii) plateau duration at the hips (Seifert,
243 Wattedled, et al., 2014; Seifert, Wattedled, et al., 2013); (iv) within-route climb time (Draper,
244 Dickson, Fryer, & Blackwell, 2011; Sanchez et al., 2010; Seifert, Wattedled, et al., 2013); (v)
245 time spent in three-hold support (Sibella et al., 2007) and; (vi) movement frequency (Cordier et
246 al., 1996).

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

255 According to Billat et al. (1995) time spent immobile reflects time under isometric
256 contraction, subsequently incurring an energy cost. However, since depending on the nature of
257 the hand holds, this time can either increase fatigue in the finger muscles (Vigouroux & Quaine,
258 2006) or provide an opportunity to allow these muscles to recover (Sanchez, Lambert, Jones, &
259 Llewellyn, 2012a), the characteristics of the route design needs to be addressed (for an innovative
260 modelling approach see, Tosi, Ricci, Rosponi, & Schena, 2011). Indeed, it has been shown that
261 periods of immobility can reflect strategic actions with respect to demands on the physiological
262 system imposed by route design (Billat et al., 1995; White & Olsen, 2010). For example,
263 different gripping techniques provide the possibility to vary the arm angle, which might afford

264 more or less rest while grasping a hold and immobile (Amca, Vigouroux, Aritan, & Berton,
 265 2012). This is also true in terms of the overall posture that climbers can adopt. For example,
 266 when sitting away from the wall with arms extended, passive forces can be exploited for
 267 remaining on the wall at a reduced energy cost (Russell et al., 2012; Zampagni et al., 2011).

268 Alternatively, White and Olson (2010) also speculated that a high immobility at the hip,
 269 in the case of bouldering, reflects an inability to perceive how to move through a route
 270 continuously, reducing performance in the activity. Sanchez et al. (2012a) provided some
 271 evidence for this argument, showing that more experienced climbers spent longer at rest locations
 272 within routes when not given an opportunity to view the route from the ground. This suggesting
 273 that immobility can indicate visual exploration of upcoming holds. Thus, individuals might
 274 benefit from periods of immobility at the hips and longer periods of reaching because exploratory
 275 actions might help to determine more effective pathways through the route (Nieuwenhuys et al.,
 276 2008; Sanchez et al., 2010; Seifert et al., 2015). Indeed, typically beginners show high levels of
 277 immobility, suggesting a lack of effective pick-up of information for perceiving climbing
 278 opportunities for route progression (Pijpers et al., 2005; Pijpers et al., 2006).

279 A key disadvantage of immobility is that classifying an individual as immobile is
 280 commonly undertaken by frame-by-frame analysis of an operator. For example, criteria for
 281 mobility have included statements like: “progress of the hips was observed” (Billat et al., 1995)
 282 whereas, criteria for static climbing have included: “no discernible movement in pelvic girdle”
 283 (White & Olsen, 2010). In an ice-climbing study, an automatic approach was taken by Seifert et
 284 al. (2014) using a definition based on a movement threshold. In this case, immobility was
 285 considered when, along the vertical axis, pelvis displacement was less than 0.15 m for durations
 286 longer than 30 s. This approach, however, required manual digitisation of the hips and was
 287 limited to analysis of vertical displacement actions of ice-climbers. Similar problems arise when
 288 manually coding limb states, where a limb is determined as moving between holds (mobile) or is
 289 in contact with a support surface (immobile) (Pijpers et al., 2006; White & Olsen, 2010). Thus,
 290 since immobility is generally determined as the lack of displacement over time, directly using
 291 velocity is a possible solution we suggest here. Specifically, for a trajectory $x : [0, T] \rightarrow R^3$, we
 292 find the thresh-hold based immobility to mobility ratio as:

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

293
 294 Equation 3

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

295 Equation 4

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

296
 297 Equation 5

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

316 **4.3 Multi-variate approaches to understanding climbing fluency**

317 Thus, we now consider in more detail how combined measures of spatial-temporal
318 indicators of performance can improve interpretation of climbing behavior using exemplary data
319 (Orth, Davids, & Seifert, 2014). In Figure 2, Panel A, both immobility (using equations 3, 4 and
320 5) and GIE (equations 1 and 2) are calculated on a climbed trajectory at three sections of a
321 beginner level route (French rating scale of difficulty = 5a). It is shown that, depending on which
322 section of the route the climber is in, the relationship between GIE and immobility can be
323 inversed. Indeed, spatial and temporal properties of behavior are probably co-adapted depending
324 on the constraints on performance (Billat et al., 1995). For example, when required to use
325 complex movements, such as when using dynamic moves, a high degree of mobility is probably
326 also important. Conversely, when using less dynamic movements, a low level of mobility may
327 help maintain a degree of stability, particularly when needing to keep the COM close to the wall
328 (Fuss, Weizman, Burr, & Niegl, 2013). If co-adaptation between GIE and IMR do support
329 efficient climbing, a clear hypothesis is that immobility and movement complexity are co-adapted
330 to maintain performance in terms of smoothness or jerk (Seifert et al., 2015; Seifert, Orth, et al.,
331 2014).

332 >>Figure 2 about here<<

333 An important limitation in understanding the results related to performance fluency such
334 as, Jerk, GIE and IMR, is that, without a consideration of the climbers intentions during periods
335 of immobility or increased entropy, these data may be mistakenly concluded as dysfunctional
336 (Seifert, Orth, et al., 2014). The study by Fryer and colleagues (2012) illustrates this point nicely.
337 In this study more experienced climbers exhibited a *greater* percentage of time spent immobile,
338 compared to less experienced individuals. After carrying out an activity analysis into the types of
339 actions undertaken during rest, it was found that the more experienced climbers were actively
340 resting during immobility, either applying chalk to their hands or shaking their hands. In this
341 example, without additional data from the activity analysis, it may have been erroneously
342 concluded that the climbers were stopping more due to the greater physiological demand imposed

343 by the route. In actual fact, the data highlighted the climbers' self-management of their internal
344 states, relative to their exploitation of opportunities for rest in the climbing route, an important
345 skill-dependent performance behavior (Fryer et al., 2012). This case exemplifies how interpreting
346 activity states of climbers can provide mechanistic insights of fluency measures (Seifert et al.,
347 2015; Seifert, Coeurjolly, et al., 2013).

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

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

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

371 **5.1 Performatory actions**

372 According to Pijpers and colleagues (2006), performatory actions are meant to reach a
373 specific goal and include: moving a hand or foot from one hold to the next to use it as support for
374 further climbing actions (Nieuwenhuys et al., 2008; Pijpers et al., 2006; White & Olsen, 2010);
375 using a hold to move the entire body vertically or ascend the route (Sanchez et al., 2012a; Seifert,
376 Wattedled, et al., 2014; Seifert, Wattedled, et al., 2013); using a hold to support recovery actions
377 (Fryer et al., 2012; Sanchez et al., 2012a); and, making visual fixations during movement at the
378 hips (Nieuwenhuys et al., 2008). Theoretically, performatory actions correspond to actions that
379 are intended for progression. If performatory actions are effective they should improve fluency,
380 by reducing the amount of time spent immobile and contributing to ongoing progression through
381 the route. For example, a climber might skip holds, use a more difficult movement (Sibella et al.,
382 2007) or use less advanced actions (Boschker & Bakker, 2002) which might result in more or less
383 fluid climbing performance.

384 **5.2 Exploratory actions**

385 Exploratory actions, on the other hand, are primarily information gathering movements
386 (Pijpers et al., 2006) where the type of information important to support perception of movement

387 opportunities (i.e., affordances) can pertain to modalities such as haptic, auditory, visual and
388 kinesthetic (Seifert, Wattebled, et al., 2014; Smyth & Waller, 1998). Exploratory actions have
389 included: when climbers explore whether a hold is within reach (Pijpers et al., 2006); when a
390 hold is touched without being used as a support (Nieuwenhuys et al., 2008; Pijpers et al., 2006;
391 Sanchez et al., 2012a; Seifert, Orth, et al., 2014; Seifert, Wattebled, et al., 2014; Seifert,
392 Wattebled, et al., 2013); when an anchorage is weighted to test its fallibility (Seifert, Wattebled,
393 et al., 2014); when tools are used to swing without a definite anchorage (Seifert, Wattebled, et al.,
394 2014; Seifert, Wattebled, L'Hermette, & Herault, 2011; Seifert, Wattebled, et al., 2013); and
395 when a visual fixation occur whilst an individual is immobile (Nieuwenhuys et al., 2008). When
396 exploratory indices increase, this is generally associated with poorer performance on measures of
397 fluency (Orth et al., 2016). For example, if a climber stops because they cannot perceive an
398 effective path through the route (Cordier et al., 1993; Sanchez et al., 2012a), this would be
399 associated with a higher frequency of hold exploration (Pijpers et al., 2006) and possibly an
400 increased GIE (Cordier, Mendès-France, Pailhous, et al., 1994). Furthermore, as exploration
401 reduces, fluency can improve (Seifert, Orth, et al., 2014; Seifert, Orth, Herault, & Davids, 2013),
402 suggesting an important relationship between exploration and performance improvement through
403 practice. For example Seifert et al. (2015) recently showed how exploration remained elevated
404 under transfer conditions after a period of variable practice (i.e., where each training session
405 involved practice on one of three different routes). In this study, implications were that potential
406 mechanisms underpinning the positive transfer in climbing were related to the efficient use of
407 exploration.

408 **6. Variability in activity states and their functionality**

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

417 Typically, total immobility is a sign of poor performance (e.g., being 'blocked'), however,
418 functional movement variability can be identified in efforts to visually explore (such as indicated
419 though head movements or gaze tracking tools). Postural exploration is probably particularly
420 relevant for beginners, as this may allow an individual to determine more efficient positions and
421 new body-wall orientations that may be important for more advanced movements (Seifert et al.,
422 2015). Another possibility discussed, has been that the individual may benefit from immobility
423 by visually exploring upcoming holds, perhaps indicated by the amount of fixations made and
424 their relative distance to the individual during immobility (Sanchez et al., 2012a).

425 Exploration can also include reaching to touch a hold but not grasping it or using it to
426 support the body weight (Seifert et al., 2015). This is probably important for perceiving accurate
427 body-scaled actions (Pijpers, Oudejans, & Bakker, 2007). Perhaps, as different techniques, such
428 as dynamic moves (Fuss et al., 2013), become part of an individual's action capabilities this
429 boundary of reachability may distinguish individuals of different skill levels. Making adjustments
430 in how a hold is grasped prior to using it, is also a form of exploration in terms of its 'grasp-
431 ability'. Prior to applying force to a hold climbers can be seen, in some cases, to make

432 adjustments to how they position their hand on a hold. Such exploratory actions may be
433 important to improve the amount of friction that can be applied to the hold (Fuss et al., 2013), or,
434 enable a qualitatively different way of using the hold such as in cases where multiple edge
435 orientations are available (Seifert, Orth, et al., 2014).

436 *** Table 1 about here ***

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

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

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

461 **7. Conclusion**

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

475 immobility should be concurrently assessed with respect to jerk. In doing so, the efficiency with
476 which a climber is able to co-adapt movement complexity with required mobility can be
477 addressed.

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

484

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629

630

631 **Figure Captions**

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

640

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

646

647 **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] 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;
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]	

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]	[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] 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. 1 and climb time
Pijpers, Oudejans,	N = 17, 11 M, 19-26	A. Route design	Climb (indoor,	Movement (hip	

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 39 th 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.

Zampagni, Brigadoi, et al. (2011) [IG] [Journal article]	subgroup.] 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) multi-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.
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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.

<p>Pijpers, Oudejans, et al. (2005) [RM] [Journal article] – Experiment 1</p>	<p>N = 8 M, 31.4 yrs±4.81SD, no experience</p>	<p>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</p>	<p>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</p>	<p>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] 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]</p>	<p>1 and climb time was significantly higher in the high condition compared to the low condition.</p>
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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)	traverse on video; each trial required 2 traversals] 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.
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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:
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	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) multi- 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]

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	required per condition] 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, Wattedled, 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, Wattedled, 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. Expert subgroup achieved greater vertical displacement, had
Seifert, Wattedled, et al. (2014) [IG] [Journal article]	N = 14; expert climber subgroup (n = 7, 32.1 ± 6.1 SD, F-RSD for rock = 7a+-	A. Skill	Climb (outdoors, ice, top-rope; 30 m high) self-preferred	Movement, verbalization (discrete actions, self-confrontation	

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 yrs 16-49, 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
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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.
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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.

648 **Table 2.** Relationships between spatiotemporal outcomes, discrete actions and climbers
 649 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 \uparrow and GIE \downarrow 2. IMR \downarrow and GIE \uparrow	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 \downarrow and GIE \downarrow	1. Fluent performance (Cordier et al., 1996).

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