

**Constraints representing a meta-stable régime facilitate exploration during practice and transfer of learning in a complex multi-articular task**

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Abstract: Previous investigations have shown that inducing meta-stability in behavior can be achieved by overlapping affordances through constraint manipulation, allowing cooperative and competitive tendencies to functionally coexist. The purpose of this paper was to test a number of conditions applying these design principles on performance during skills practice and transfer. Of additional interest, was whether the existing skill level interacted with the environmental properties of the experimental tasks (varying indoor climbing routes). Two skill groups practised on three routes per session over four separate sessions. At the end of the final session, climbers undertook a transfer test. Routes, matched for difficulty, were manipulated in terms of hand-hold design. Route-1 and Route-2 were designed with holds with a single graspable edge, aligned entirely parallel or perpendicular to the ground plane respectively. Route-3 had at each hold, two graspable edges (one parallel and one perpendicular to the ground plane). Behavioral exploration at the hip and hands were largest under the metastable condition (Route-3). Skill level also interacted with route properties during practice and influenced transfer. Data suggest meta-stability induces exploratory behaviors. Less skilled individuals explore both hand and hip levels, whereas, more experienced climbers explore at the hip level.

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18

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21 be achieved by overlapping affordances through constraint manipulation,  
22 allowing cooperative and competitive tendencies to functionally coexist. The  
23 purpose of this paper was to test a number of conditions applying these design  
24 principles on performance during skills practice and transfer. Of additional  
25 interest, was whether the existing skill level interacted with the environmental  
26 properties of the experimental tasks (varying indoor climbing routes). Two skill  
27 groups practised on three routes per session over four separate sessions. At the  
28 end of the final session, climbers undertook a transfer test. Routes, matched for  
29 difficulty, were manipulated in terms of hand-hold design. Route-1 and Route-2  
30 were designed with holds with a single graspable edge, aligned entirely parallel  
31 or perpendicular to the ground plane respectively. Route-3 had at each hold, two  
32 graspable edges (one parallel and one perpendicular to the ground plane).  
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34 condition (Route-3). Skill level also interacted with route properties during  
35 practice and influenced transfer. Data suggest meta-stability induces exploratory  
36 behaviors. Less skilled individuals explore both hand and hip levels, whereas,  
37 more experienced climbers explore at the hip level.

38 **Key words:** Skill, Affordances, Practice, Transfer, Meta-stability, Constraints

39

## 40 **1.1 Introduction**

41 Learning complex multi-articular actions is influenced by the specific  
42 experiences of an individual under constraints present during practice (Seifert,  
43 Button, & Davids, 2013). Internal and external constraints on performance are  
44 inherently uncertain, requiring adaptation of movement patterns to regulate  
45 actions and their stability (Newell, 1991). Designing uncertainty into a practice  
46 environment may be functionally specific (supporting goal achievement) for  
47 performance in contexts towards which the **transfer of skill or learning is**  
48 **intended (for definitions, see Carroll, Benjamin, Stephan, & Carson, 2001; for**  
49 **experimental data, see Travassos, Duarte, Vilar, Davids, & Araújo, 2012).** Induced  
50 uncertainty can be designed into learning programmes through constraints  
51 manipulation at the task, individual and/or environmental levels (Chow, Davids,  
52 Button, & Koh, 2008; Orth, Davids, & Seifert, 2015; Ranganathan & Newell, 2013).  
53 **A hallmark feature of practice under such constraints is movement variability.**  
54 **Movement variability can be functionally characterized in different ways such as**  
55 noise (Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009), movement  
56 regulation (Pinder, Davids, & Renshaw, 2012), health (Harbourne & Stergiou,  
57 2009), complexity (Travassos et al., 2012) or exploration during learning  
58 (Cordier, Mendès-France, Pailhous, & Bolon, 1994).

59

60 **An important issue is to investigate the functional role of induced movement**  
61 **variability throughout practice in order to address potential mechanisms**  
62 **underpinning rate of learning and transfer effects (Pacheco & Newell, 2015;**  
63 **Seifert, Wattebled, et al., 2016).** For example, on the one hand, random variability

64 appears to promote exploration (Huet et al., 2011; Schöllhorn et al., 2009) and  
65 maintain adaptive capacity in a movement system (Tumer & Brainard, 2007). On  
66 the other hand, *constrained variability* may allow the practitioner to adapt to  
67 individual factors such as skill (Davids, Araújo, Hristovski, Passos, & Chow, 2012),  
68 supporting a fit between the individual and context dependent factors that may  
69 help avoid deleterious effects of random processes (Simonton, 2003).

70

71 Inducing learning can be facilitated by challenging the equilibrium of stable  
72 movement patterns to invite other movement patterns to learn (Chow, Davids,  
73 Hristovski, Araújo, & Passos, 2011). Here we investigated how this process may  
74 be induced under conditions of meta-stability (Pinder et al., 2012). Specifically,  
75 meta-stable movement coordination régimes refer to regions of performance  
76 where individual and environmental influences on performance simultaneously  
77 coexist. This leads to the coexistence of competitive (less stable) and cooperative  
78 (more stable) coordination tendencies where neurobiological components (such  
79 as central nervous system components) support adaptation and emergence of  
80 new behaviors (Kelso, 2012).

81

82 Within the ecological dynamics framework (see, Davids, Araújo, Seifert, & Orth,  
83 2015), a key assumption is that acquiring skill in multi-articular tasks involves  
84 the potential for different actions that can be adopted by individuals for  
85 achieving the same performance outcomes, reflecting inherent degeneracy of  
86 each individual movement system (Edelman & Gally, 2001; Mason, 2010). As the  
87 individual adapts to the dynamic environment, system degrees of freedom are  
88 exploited through continuous re-organisation as they utilise affordances (i.e.

89 **perceived behavioural opportunities**). Harnessing system degeneracy can help  
90 people manage in uncertain environments where more movement variability can  
91 reflect greater levels of exploration (Chow et al., 2008; Hristovski, Davids, Araújo,  
92 & Button, 2006; Pinder et al., 2012). By manipulating affordance landscapes (cf.  
93 Rietveld & Kiverstein, 2014), competitive (less stable) and cooperative (more  
94 stable) coordination tendencies can be represented, inviting exploration or  
95 learning processes (Seifert, Komar, Araújo, & Davids, 2016).

96

97 Operationally, an important indicator a system's stability and the related capacity  
98 in harnessing system degeneracy, is the degree of entropy that a constrained  
99 system exhibits (Edelman & Gally, 2001). For example, the geometric index of  
100 entropy (GIE) was developed by Cordier et al. (1994) as a spatial measure of  
101 entropy in climbed trajectories (i.e., the pathway of climbers' estimated hip  
102 positions, projected onto the surface of a climbing wall as a 2D coordinate  
103 system). Low levels of GIE suggesting behavioral certainty and stability  
104 (observed in straight forward and fluent performance behaviors) whilst, higher  
105 levels of entropy indicate behavioral uncertainty and instability (more complex,  
106 chaotic or less fluent movements) **(for a recent review see, Orth, Button, Davids,**  
107 **& Seifert, 2016)**. **Theoretically, measures such as GIE provide an indication of**  
108 **how effectively degeneracy is exploited in managing system stability (e.g., such as**  
109 **to avoid falling during a climbing activity) (Cordier, Mendès-France, Bolon, &**  
110 **Pailhous, 1994; Edelman & Gally, 2001)**.

111

112 **Of additional operational concern is,** that, previous investigations have shown  
113 individuals can be positioned to perform under a meta-stable regime by

114 manipulating constraints so as to create an overlap in qualitatively distinct  
115 affordances (Hristovski et al., 2006; Pinder et al., 2012). For example, Hristovski  
116 et al. (2006) observed that designs which altered arm scaled distance of boxers  
117 to a punch bag during practice facilitated affordances to constrain the emergence  
118 of a rich range of hitting actions. These results showed that a feature of practice  
119 in a meta-stable regime is for different patterns of movement coordination to be  
120 explored spontaneously (Hristovski et al., 2006). Although, in operational terms,  
121 designing constraints that induce meta-stable behavior appears to be  
122 understood, the functionality of this system state to the learner is unclear.

123

124 Indeed, it is currently untested how individuals with different levels of skill might  
125 respond to practice under meta-stable design constraints. For instance, whilst  
126 extensive exploration of different actions can emerge under novel practice task  
127 constraints in inexperienced individuals (Chow et al., 2008), experienced  
128 individuals under similar constraints show minimal exploration (Chow, Davids,  
129 Button, & Koh, 2006; Seifert, Wattebled, et al., 2014). A feature of experienced  
130 individuals, in multi-articular tasks, is an immediate availability of movement  
131 patterns which support a functional response to satisfy interacting task and  
132 environmental constraints (Sanchez & Dauby, 2009; Seifert, Wattebled, et al.,  
133 2014). Hence, the learning dynamics of an individual in a meta-stable regime  
134 need to be investigated relative to his/her existing experience levels (Seifert,  
135 Wattebled, et al., 2013).

136

137 In this study, practice was manipulated to induce meta-stability in performance  
138 of the complex motor coordination task of climbing to observe exploratory



139 behaviors in experienced and less experienced individuals. Meta-stability was  
140 represented in an indoor climbing task by increasing the number of available  
141 climbing affordances in the environment, allowing their usability to overlap. In  
142 the task of climbing, affordances refer to properties of a wall that are perceived  
143 by individuals for supporting grasping and climbing actions and that are also  
144 experience-dependent (Boschker, Bakker, & Michaels, 2002). Importantly, even  
145 novice climbers can perceive climbing affordances if they are within their ability  
146 level (Pezzulo, Barca, Bocconi, & Borghi, 2010), suggesting the potential to  
147 transfer fundamental capabilities such as ladder climbing to novel climbing  
148 environments (Seifert, Wattebled, et al., 2016). In this study, overhand- and side-  
149 orientated grasping actions were designed into the environment by modifying  
150 the number of edges and orientation of hand holds. Specifically, overhand  
151 grasping actions were supported by designing holds with a graspable edge that  
152 ran parallel to the ground. Vertically aligned grasping actions were supported by  
153 designing holds with graspable edges that ran perpendicular to the ground. It  
154 was anticipated that meta-stability in behavior would emerge in climber-  
155 environment systems if, at each hold, both an over-hand and a vertically aligned  
156 grip were available (note that a number of pilot studies have been undertaken in  
157 support of these assumptions, see Seifert, Boulanger, Orth, & Davids, 2015;  
158 Seifert, Orth, et al., 2014; Seifert, Orth, Hérault, & Davids, 2013).

159

160 The hypotheses included: 1) both skill groups would be induced to learn on the  
161 route where, at each hold, multiple actions were functionally available; 2) less  
162 experienced performers would show learning effects on routes where only a  
163 single action was supported, that was specific to climbing, whereas more

164 experienced climbers would not, and; 3), that transfer of skill would be facilitated  
165 by experience on the different routes.

## 166 **2.1 Methods**

### 167 **2.1.1 Participants**

168 A total of 14 participants were recruited based on their self-reported red-point  
169 levels (where red-point refers to route climbing ability after practice, see (Draper,  
170 Dickson, et al., 2011)). One group, (the less-skill group), comprised participants  
171 (n=7),  $20.9 \pm 5.7$  years; mean height:  $165.4 \pm 8.5$  cm; mean weight:  $69.1 \pm 6.8$  kg,  
172 with a level 5b-5c on the French rating scale of difficulty (F-RSD) (i.e. a difficulty  
173 scaling from 1-9, (Delignières, Famose, Thépaut-Mathieu, & Fleurance, 1993)).  
174 These individuals had no more than 10 hours of training experience on indoor  
175 climbing walls and had been trained on the safe use of climbing equipment under  
176 top-roped conditions (detailed below). With respect to the intervention routes,  
177 this group might be considered as corresponding to a coordination stage of  
178 learning (Newell, 1996). A second, more-skilled, group of seven individuals ( $24.9$   
179  $\pm 4.7$  years; mean height:  $175.4 \pm 6.8$  cm; mean weight:  $69.1 \pm 6.8$  kg), were  
180 recruited on the basis of having a F-RSD level between 6a-6b (Draper, Canalejo, et  
181 al., 2011; Draper, Dickson, et al., 2011). These participants reported roughly 3  
182 years of climbing experience and might be considered at a control stage of  
183 learning with respect to the intervention routes. Participants provided informed  
184 consent and the study conducted with ethical approval.

### 185 **2.1.2 Experimental Procedure**

186 Data were collected on four separate days, with at least two days separating each  
187 session and over a two week period. All sessions started with participants being  
188 fitted with a harness and climbing shoes. After a climbing specific warm up, they

189 completed three previewed, top-roped climbs. Each climb was on a different  
190 experimental route, the order of which was counterbalanced so that the order of  
191 treatment of each route from one session to the next was diversified across  
192 participants. Between each climb, a seated 5-minute rest was enforced. On the  
193 fourth session, climbers also undertook a transfer test at the end. For each climb  
194 participants were instructed to self-pace their ascent, with the following task-  
195 goal: explore the way to climb in the most *fluent* manner, i.e., without falling  
196 down and by minimizing pauses in the rate of body displacement vertically on  
197 the wall surface.

### 198 **2.1.3 Instrumentation**

199 Participants were equipped with an LED marker positioned at the centre of the  
200 harness at the posterior body midline. Video footage of each ascent was captured  
201 with a frontal camera (Sony EX-View Super HAD, Effective pixels:768x520, that  
202 allowed a resolution of 560 lines, with a 2.6mm lens that offered a 120° angle of  
203 view) fixed 9.5m away from the climbing wall and at a distance of 5.4m from the  
204 ground. A calibration frame, 10.3m vertical x 3m horizontal and composed by 20  
205 markers, was used to correct for distortion and calibrate the digitized trajectory from  
206 pixels to metres (done using a semi-automatic tracking procedure with the  
207 Kinovea 8.15 software).

### 208 **2.1.4 Behavioral data**

209 Behavioral data that reflected learning in the form of exploratory activities were  
210 collected in analyses of hand and hip movements. Specifically, exploration was  
211 indexed using: (i) the total number of exploratory actions with the hands (where  
212 a hold is touched by the hand, and during this contact not subsequently used to  
213 move or weight the body and the next action of the hand was either to move to

214 another hold or to release the hold and then change the hand's position on the  
215 same hold; and (ii), the geometric index of entropy (GIE), calculated from the  
216 trajectory of the climbers' hip (using the 2D trajectory of an LED positioned at  
217 the hip projected onto the plane of the climbing wall during each ascent). Also  
218 note that additional performance data were collected, including: falls and the  
219 relative use of hand holds (ratio of number of holds used to holds contained in  
220 the route, or up to the point of falling).

221

222 **Geometric index of entropy.** More formally, the GIE is a ratio of the path length of  
223 a trajectory to the perimeter of its convex hull (Cordier, Mendès-France, Pailhous,  
224 et al., 1994) and is a uniquely spatial indicator of performance behaviour. GIE is  
225 given for a given trajectory  $x : [O, T] \rightarrow R^3$ , letting  $\Delta x$  be the trajectory length:

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

226

(1)

227 and  $\Delta c(x)$  the convex hull perimeter.

228 The GIE is then given by:

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

229

(2)

230 noting that the division by  $\log(2)$  places the GIE in dimensionless terms (bits) .

231 Thus, in recalling the discussion above, GIE can assess, in spatial terms, the  
232 amount of fluency of a curved trajectory. The higher the entropy value, the higher  
233 the disorder of the climbing trajectory (Cordier, Mendès-France, Bolon, et al.,  
234 1994). On the other hand, the lower the GIE value the more simple and straight

235 forward the trajectory (Sibella, Frosio, Schena, & Borghese, 2007). When  
236 considered over successive trials GIE is also a useful measure of learning because  
237 of it relates to route finding behaviors (Boschker & Bakker, 2002; Cordier,  
238 Mendès-France, Pailhous, et al., 1994) indicating the ability of climbers to pick up  
239 information from a surface to find paths through the route that afford fluid  
240 continuous traversal (Cordier, Mendès-France, Pailhous, et al., 1994). For a visual  
241 example of GIE the reader is referred to Sibella et al., (2007).

242

243 **Touch and withdraw.** Pijpers and colleagues (Pijpers, Oudejans, Bakker, & Beek,  
244 2006) also distinguished between exploratory and performatory movements at  
245 the hand level, revealing behavioural certainty specifically with regards to hold  
246 use. Climbers tend to reduce the time spent in states of three-limb support  
247 because it increases the force required at other limbs to remain fixed to the wall  
248 (Bourdin, Teasdale, & Nougier, 1998; Sibella et al., 2007), tending to limit  
249 exploration, where a hold is touched but not subsequently used to support the  
250 body weight, to periods of uncertainty. Following Pijpers et al., (2006), the  
251 number of touch and withdraw actions were computed as the total number of  
252 actions made at the hands for each climb, where a hand hold was touched and  
253 not subsequently used to support hip displacement and which the following  
254 action with the same hand was to withdraw contact from the hold to then make a  
255 new contact with the same or another hold.

### 256 **2.1.5 Routes**

257 Three experimental routes were designed based on the orientation and number  
258 of graspable edges at each hold (20 holds per route were used). Route-1  
259 contained only holds with a horizontally-graspable edge (with the knuckles

260 running parallel to the ground plane). Each hold in Route-2 had a single,  
261 vertically-graspable edge (with the knuckles running perpendicular to the  
262 ground plane) and, Route-3 included at each hold a graspable edge that was  
263 horizontally aligned in addition to an edge that was vertically-graspable. This  
264 latter route was considered to represent meta-stability as it afforded the choice  
265 of two grasping actions at each hold i.e. those grasping actions supported by  
266 Route-1 and Route-2 (see Figure 1 for details). The transfer route (Route-4) was  
267 made up of six horizontal holds, and seven vertical holds, as well as seven holds  
268 with both edges. The transfer test was designed to determine whether  
269 experience on the practice routes supported performance on the new route  
270 finding problem. The transfer route was also designed to represent the different  
271 constraints experienced during practice and primarily the uncertainty involved  
272 in route finding on a new route. Furthermore, the aim was not to expose  
273 participants to qualitatively different technical demands which is why similar  
274 grasping opportunities to practice were represented. Each route was designed by  
275 an experienced setter and the difficulty level held constant at level 5b F-RSD. The  
276 ratings were confirmed by consensus with two additional and fully qualified  
277 route setters.

278 >>Figure 1<<

### 279 **2.1.6 Data analysis**

280 A mixed methods ANOVA for the trial (4) x route (3) x group (2) effects were  
281 used to evaluate the learning effect separately for the GIE and touch and  
282 withdraw data. Prior to undertaking the analysis Mauchley's test was used and  
283 confirmed homogeneity of sphericity for the repeated measures. For explaining  
284 the size and nature of differences, as well as interaction effects, planned contrasts

285 were then performed. Following effects are reported significant at  $p \leq .05$ , noting  
286 that effect sizes were only calculated from contrasts and main effects that  
287 involved a single degree of freedom, see (Kirk, 1996)).

288

289 Contrasts were designed with the expectations that entropy values and hold  
290 exploration would reduce with practice, that more complex route design would  
291 increase entropy and hold exploration, and that more experienced climbers  
292 would display lower entropy and hold exploration. Of particular interest was  
293 whether interaction effects between route, trial number and skill would emerge  
294 to suggest that skill level interacted with specific route design properties,  
295 influencing whether learning effects were induced. For follow-up tests,  
296 Bonferroni adjustments controlled for inflation of the type I error. Being based on  
297 categorical data, instances of falls were assessed using non-parametric tests  
298 (Freidman's and Wilcoxon's) and the data with respect to the number of holds  
299 used, relative to those available, were assessed with repeated measures ANOVA.

300

301 To assess transfer, an omnibus of t-tests was planned on both variables at the  
302 within- (between Trial 4 on the double-edged route and the transfer route) and  
303 between-group levels of analysis (less skill vs. more skill) with Bonferroni  
304 adjustments. We chose to compare Trial-1 on the double edged route and the  
305 Transfer test because these represented on-sight conditions under the most  
306 complex or uncertain conditions (i.e., since both involved double-edged holds).

307

308 **3.1 Results**

309 The mean values and their respective standard errors of the mean, and  
310 significant main effects and interaction effects are summarised in Figure 2 where  
311 in, Graphs A-E refer to the analysis of hip entropy and in Graphs F-J relate to hand  
312 hold exploration data.

313

314 >>Figure 2<<

315

316 The following results are organized in relation to the research questions of  
317 interest, that: 1) both groups would be induced to learn on the meta-stable route;  
318 2) the less experienced group would show learning effects on routes that require  
319 climbing specific experience whereas, the more experienced climbers would not;  
320 and 3), that transfer would be supported in both groups.

321 **3.1.1 Effect of practice on meta-stable route**

322 There were significant interaction effects at both the route x practice and group x  
323 practice level for the outcome of entropy:  $F(3, 36) = 2.274, p = .05, r = .40$ ;  $F(3,$   
324  $36) = 6.256, p = .002$ , respectively. However for the outcome of hand exploration  
325 there was only a significant interaction at the group x practice level;  $F(3, 36) =$   
326  $3.323, p = .03$ . In examining the estimated marginal means for entropy and hold  
327 exploration for the route by practice interaction (Figure 2, graphs D and I  
328 respectively) it is clear that the less experience climbers showed a distinct global  
329 learning effect whereas the more experienced climbers did not. For the condition  
330 by practice effect, the marginal means show that primarily for the double edged  
331 and vertical routes there was a distinct trend from higher to lower amounts of



332 entropy and hand exploration seen with practice (Figure 2, graphs E and J  
333 respectively). In order to determine if both groups showed a learning effect on  
334 the double-edged route follow up tests were undertaken where repeated  
335 measures ANOVA were used for each condition across each group. These results  
336 are summarised Table 1.

337

338 >>Table 1<<

339

340 The significant findings showed that for the more experienced climbers, the  
341 double edged condition induced a learning effect,  $F(3, 18) = 6.258, p = .004$ .  
342 Planned contrasts comparing Trial 1 to Trial 4, Trial 2 to Trial 4 and Trial 3 to  
343 Trial 4, showed that this effect was primarily driven by the significantly higher  
344 GIE at Trial 1,  $F(1, 6) = 26.078, p = .002, r = .902$ .

345

346 For the less experienced group, a significant learning effect was also shown for  
347 the double edged route,  $F(3, 18) = 5.820, p = .006$ . The planned contrasts  
348 indicated the effect of practice on the double-edged route for the less  
349 experienced group was driven by the significantly higher entropy at Trial 1  
350 compared to Trial 4,  $F(1, 6) = 20.623, p = .004, r = .880$ . Additionally, the less  
351 experienced group showed a significant learning effect on hold exploration on  
352 the double edged route  $F(3, 18) = 7.000, p = .003$ , with planned contrast showing  
353 that at Trial 1 exploration was significantly higher than Trial 4,  $F(1, 6) = 6.299, p$   
354  $= .046, r = .716$ .

### 355 **3.1.2 Effect of route design and skill on learning**

356 The findings shown in Table 1 also support the hypotheses that existing skill

357 determined whether a specific route induced learning or not. In the more  
358 experienced group neither the horizontal route,  $F(3, 18) = 1.347$ ,  $p = .291$ , or the  
359 vertical route,  $F(3, 18) = 0.987$ ,  $p = .421$ , induced a learning effect, whereas the  
360 double edged route showed a significant learning effect with regard to entropy  
361 (Table 1). There were no significant effects related to hand hold exploration  
362 across any route in the experienced group.

363

364 In contrast, in the less experienced group, both the double edged route and the  
365 vertical edged route,  $F(3, 18) = 6.552$ ,  $p = .003$ , induced a learning effect, whereas  
366 the horizontal edged condition showed no significant effect,  $F(3, 18) = 1.574$ ,  $p$   
367  $= .230$ . Similar to the double edged route, on the vertical edged route, the planned  
368 contrasts showed that entropy was significantly higher at Trial 1 compared to  
369 Trial 4,  $F(1, 6) = 5.847$ ,  $p = .052$ ,  $r = .703$ .

370

371 Wilcoxon's tests, examining route effects, also showed that no route was  
372 associated with having a significantly greater probability of falls compared to any  
373 other. **Throughout the course of practice**, there were 4 falls on the horizontal  
374 (across 28 trials of practice per route), 7 on the vertical and 13 in total on the  
375 double edged route. Further at the level of practice (excluding route specific  
376 effects), there were 10 falls at Trial 1, 8 falls at Trial 2, 4 falls at Trial 3, and 2 falls  
377 at **Trial 4**. It can also be noted that Wilcoxon's test between Trial 1 and Trial 4  
378 showed a significant reduction of falls,  $z = -2.00$ ,  $p = .046$  when considering only  
379 the effect of practice.

### 380 **3.1.3 Transfer effect**

381 To address the impact of practice on performance and behavior during transfer,

382 comparisons were undertaken on entropy and hand hold exploration (see Table  
383 2). The key findings revealed that: a) neither entropy or hand hold exploration  
384 was significant in distinguishing between groups at the final trial of practice on  
385 the double edged route; b) neither between group (less vs. more skill), or  
386 between condition (trial 4 on the double edged route vs. transfer route) entropy  
387 were significantly different; c) only hand exploration distinguished between the  
388 two groups (less vs. more skill) under the transfer test conditions,  $t(12) = 4.47$ ,  $p$   
389  $= .001$ ,  $r = .79$ , and; d) in the less experienced group, the hand hold exploration  
390 significantly increasing under transfer conditions relative to the amount of  
391 exploration on the fourth trial of practice on the double edged route,  $t(6) = 4.804$ ,  
392  $p = .003$ ,  $r = .89$ . This observation suggests that the experienced group  
393 transferred skill in terms of low entropy. In contrast, the less experienced group  
394 showed a capacity to transfer low entropy at the hip, however showing a high  
395 amount hand hold exploration. In fact, it was the two outcome variables in  
396 combination that differentiated the two groups under transfer conditions. With  
397 regard to falls, there were no significant effect between the first trial of the  
398 double edged route and the transfer route in the less experienced group, whilst  
399 none of the more experienced climbers fell. Nor were significantly more hand  
400 holds used in the Transfer route in comparison to Trial 1 of the double edged  
401 route.

402 >>Table 2<<

403

404

405 **4.1 Discussion**

406 The purpose of this study was to consider potential interactions between prior  
407 experience and environmental properties on behavioral certainty during  
408 learning and transfer, when performing an indoor climbing task. The first  
409 hypothesis, that learning could be induced using meta-stable design principles  
410 was confirmed, and regardless of the initial skill level of the individuals. However,  
411 this evidence was only shown at the hip level in more skilled climbers, as  
412 opposed to both at the hip and hand levels in less experienced climbers.

413

414 The second hypothesis was also confirmed, with data suggesting that the existing  
415 experience level of the participants interacted with specific route design  
416 properties. It was particularly interesting that findings suggested that knowledge  
417 of the vertically orientated grasping pattern of coordination needs to be acquired  
418 through experience where only the less experienced group showed a learning  
419 effect on this route.

420

421 Finally, also confirmed is the third question, that, transfer contexts designed to  
422 represent similar levels of environmental variability, as those experienced under  
423 practice constraints, can facilitate the transfer of skill. Of particular interest was  
424 that transfer of skill seemed dependent on both entropy at the hip and hand hold  
425 exploration in combination. This finding also suggesting that the initial level of  
426 skill of individuals prior to practice, influenced the nature of the transfer.

427 Specifically, the less experienced climbers, appeared to learn how to explore at  
428 the hand level, without increasing hip entropy (i.e. they learnt to explore more

429 efficiently).

430 ***4.1.1 Meta-stable design properties induces learning in less and more skilled***  
431 ***individuals***

432 The data showed that both groups were induced to go through a learning process  
433 (a general reduction in behavioral uncertainty) when practising on the route that  
434 supported, at each hold, a choice of grasping actions, one choice supporting an  
435 over-hand grip and one that supported a vertical-hand grip (see Table 1, and  
436 refer to Figure 3, Graphs A and B). Noting the shape of the learning curves for GIE  
437 outcomes at the hip, it appears that the behavioral changes shared similar rates  
438 of improvement. However, at the hand level, exploratory activities were very  
439 different between groups (Figure 3, Graphs C and D). The less experienced  
440 climbers exhibited much greater levels of touching, but not grasping holds  
441 (Figure 3, Graphs D). This finding suggests both general (route finding) and  
442 differential (hold graspability) effects of how the double edged route might have  
443 facilitated an improvement in performance through practice dependent on initial  
444 skill level.

445  
446 >>Figure 3<<

447  
448 Indeed, the clearest indication of a skill dependent effect can be related to the  
449 overall larger amount of hand hold exploration shown by the less experienced  
450 group compared to the more experienced group. These data suggest that  
451 determining how to grasp and/or use holds were challenged in the less  
452 experienced group. In the more experienced group, it seems the overt hold  
453 exploration was unnecessary, possibly because the capacity to perceive  
454 information related to hold graspability had already been adapted through  
455 experience (Bläsing, Gldenpenning, Koester, & Schack, 2014; Boschker et al.,

456 2002; Pezzulo et al., 2010). However, it is not clear exactly why learning (in  
457 terms of improved fluency at the hip) was induced in the more experienced  
458 climbers, but, one interpretation of the data would suggest that presentation of  
459 choice at each hold induced a route finding problem (Cordier, Mendès-France,  
460 Pailhous, et al., 1994). Future research at different levels, such as gaze, which can  
461 also be characterized by exploratory behaviors might support these ideas  
462 (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008; Sanchez, Lambert, Jones, &  
463 Llewellyn, 2012).

#### 464 **4.1.2 Environmental design properties interact with the intrinsic dynamics of** 465 **individuals to shape the nature of learning**

466 The experience levels of the participants interacted with specific route design  
467 properties, influencing the nature of the transfer to each practice condition. The  
468 vertical and horizontal routes did not induce learning in the experienced group,  
469 suggesting these behaviors were already stable. In contrast, the vertical *and*  
470 double edged routes induced greater amounts of behavioral variability, both at  
471 the hand and hip levels, in the less experienced group compared to the horizontal  
472 route (see Table 1 and Figure 3, Graphs B and D).

473  
474 The significant differences between both the vertical and double edged routes,  
475 compared to the horizontal edged route, suggest that the grasping actions  
476 associated with vertically aligned edges during route finding appeared to require  
477 experience. On the other hand, the grasping actions for horizontally aligned holds  
478 appeared to be easier to transfer to the route finding task. The less experienced  
479 climbers' transfer of skill to the horizontal route can be explained as a function  
480 these grasping opportunities perhaps matching fundamentally stable grasping  
481 actions, such as ladder climbing (Newell, 1996; Seifert, Wattedled, et al., 2016).

482 This result is similar to other findings showing that inexperienced individuals  
483 climbing ice-falls tended to adopt a similar movement pattern where the body  
484 resembles an X-shape (Seifert, Wattedled, et al., 2014; Seifert, Wattedled, et al.,  
485 2016).

486  
487 It was somewhat surprising, that, in the less experienced group, the vertical and  
488 double edged route induced fairly similar amounts of exploration at the hand and  
489 hip levels. It **would be** expected that the double edged route could facilitate  
490 greater exploration with the hands, simply by virtue of there being more edges.  
491 Whilst this effect was statistically significant, the size of the difference was not so  
492 large as to overly **emphasize** the difference between vertical and double edged  
493 routes on hold exploration. For example, on the double edged route, the use of  
494 more unstable vertical grasping actions could have been explored whilst falling  
495 back to the use of the more stable horizontal actions, yet this opportunity was  
496 not exploited to a large effect relative the vertical edge condition. Related to this  
497 concern is the fact that a similar level of hand hold exploration was occurring on  
498 the vertical edged route, which in contrast, had half the number of edges. The  
499 finding that both the vertical and the double edged route induced similar levels of  
500 hold exploration may indicate that the need to stabilize vertical grasping was  
501 perhaps driving haptic exploration, but was being limited by the task of route  
502 finding. Specifically, if route finding becomes inefficient, this places constraints  
503 on the individual both at the postural and limb organization levels, possibly  
504 increasing the likelihood of falling (Bourdin et al., 1998). Indeed both conditions  
505 (vertical and double) were not differentiated by the amount of entropy at the hip  
506 in any significant respect and furthermore, as practice continued, hand hold

507 exploration remained significantly elevated in comparison to hip entropy which,  
508 in contrast, systematically reduced. This latter point suggesting, that, as the route  
509 finding problem was relaxed, hold exploration levels were sustained, indicating  
510 an ongoing learning effect at the hand level. One hypothesis might be, that, as the  
511 less experienced climbers determined an efficient way to regulate the pathway at  
512 the hip, their continued exploration at the hand hold level suggests an ongoing  
513 concern with how to grasp or use holds in different ways (Seifert, Wattedled, et  
514 al., 2014).

#### 515 ***4.1.3 Future challenges in understanding the transfer of skill***

516 Here we consider implications in the more experienced group that the transfer of  
517 skill might be accounted for by the learning effect induced on the double edged  
518 route. Arguably, if the climbers had not practised on the double edged route,  
519 climbing fluency would have likely worsened to levels similar to those observed  
520 on the first practice trial on the double edged route. This interpretation of the  
521 data is supported by the observation that neither the vertical, nor the horizontal  
522 routes, induced increased entropy levels at Trial 1. Rather, exposure to increased  
523 uncertainty on the double edged route during practice may have supported  
524 performance on the transfer route. The mechanism for this transfer effect may be  
525 the behavioural variability induced by choice posed at each hold in the double  
526 edged route. Future research should consider adapting an independent group  
527 design in order to determine if a specific condition underpinned the transfer  
528 effects.

529

530 On the other hand, the less experienced climbers also showed a capacity to  
531 transfer climbing fluency at the level of the hip, but, in contrast to the more



532 experienced climbers, they continued to exhibit a large amount of hand hold  
533 exploration (see Figure 3, Graphs E and F). This was striking, because, early in  
534 practice, both hand hold exploration and hip entropy were high, whereas in  
535 transfer, high hand hold exploration was associated with low entropy. This  
536 finding suggests the possibility that exploration at the level of the hand  
537 supported the transfer of route finding in the less experienced climbers. And  
538 indeed, the climbers who demonstrated the most exploration during transfer also  
539 successfully transferred performance (i.e. they did not fall, see Figure 3, Graph E  
540 and F). This finding is in stark contrast to the first trial of practice, where the  
541 more successful climbers demonstrated less exploration at the hand levels. On  
542 the transfer route, in this study, the evidence suggests that the reason climbers  
543 effectively transferred skill was because of a capability to explore at the hand  
544 level without disrupting hip stability.

545

546 In the case of the less experienced group, learning was induced in both vertical  
547 and double edged conditions. Because, at each session practice on each route was  
548 counter-balanced, this reflects variable practice conditions and may be the main  
549 the reason underpinning the transfer effects (Chow, 2013; Ranganathan &  
550 Newell, 2013). Similar to the discussion above, future research should consider  
551 implementing an independent group design in order to determine if a specific  
552 condition underpinned the transfer effects. For instance it may be for the less  
553 experienced climbers either the double edged or vertical edged route could have  
554 driven the transfer effect.

555

556 In general, the findings of this study open up a number of research questions

557 related to the different forms of behavioural variability that can support  
558 performance under representative transfer conditions. Specifically, in the  
559 inexperienced group of climbers, it is impossible to determine whether  
560 exploration transferred due to exposure to any one of the three routes and future  
561 work should be aimed at determining whether exploration induced by practice  
562 on specific route designs is the main mechanism that supports transfer.

### 563 **5.1 Conclusions**

564 The key findings reported in this study are that, in a task involving climbing  
565 practice, learning emerged at the hands and body levels. The level and rate at  
566 which learning occurred was shown to be dependent on the existing skill levels  
567 of the climbers. Skill was shown to moderate the stability of specific climbing  
568 actions, where over-hand and vertically orientated grasping were immediately  
569 stable in experienced individuals and only over-hand grasping was stable in less  
570 skilled individuals. Learning was induced in a group of experienced climbers by  
571 manipulating the number of actions available and not by requiring them to learn  
572 new, unfamiliar climbing affordances, as in the less experienced group. It is  
573 argued that this practice design supported performance under transfer  
574 conditions in experienced climbers. On the other hand, performance under  
575 transfer in less experienced individuals was related to more exploratory actions  
576 at the hands.

577

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725

**Reply letter re: manuscript No.: HMS-D-15-00043**

Dear Professor Andreas Daffertshofer,

Please find below comments addressed for the manuscript, No.: HMS-D-15-00043 'Constraints representing a meta-stable régime facilitate exploration during practice and transfer of learning in a complex multi-articular task'.

Thank you again for taking the time to revise, make comment and coordinate comments on behalf of the reviewers.

Please see our responses detailed below which are given as tabbed text.

Changes are also highlighted in the manuscript.

Sincerely, on behalf of the authors,

Dominic Orth

**Response**

Section editor: Two expert reviewers assessed the manuscript and provided several detailed comments that can certainly help improving it. In particular reviewer #1 listed very detailed issues that ought to be addressed prior to considering the manuscript for publication in HMS. I would like to take the opportunity to stress the need for a detailed explanation of the encounter entropy measure and its precise implementation. The GIE is a mere measure of the path length relative to its convex hull and I cannot see why this would measure entropy. Entropy is a measure of disorder by virtue of a concave function. The classic (extensive) form is that of Boltzmann measuring the order in a statistical ensemble as  $-\sum(p \log p)$ . This, by the way, has nothing to do with energy (in physics entropy and energy are both consider integrals of motion but they are independent apart from Landauer's erasure principle). How does the GIE fit in this view? I trust that the reports below further suffice to provide a properly revised version.

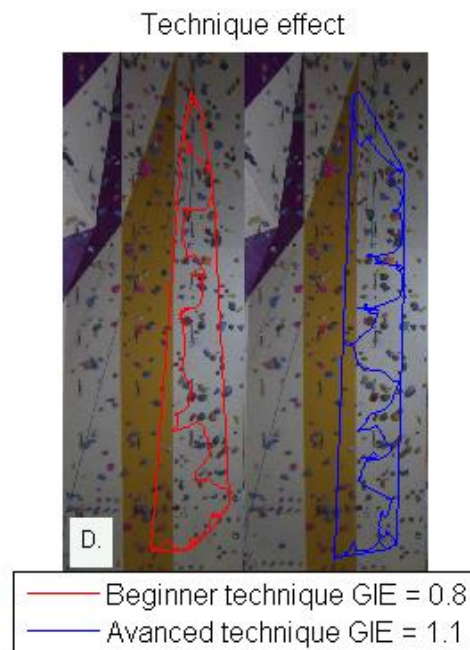
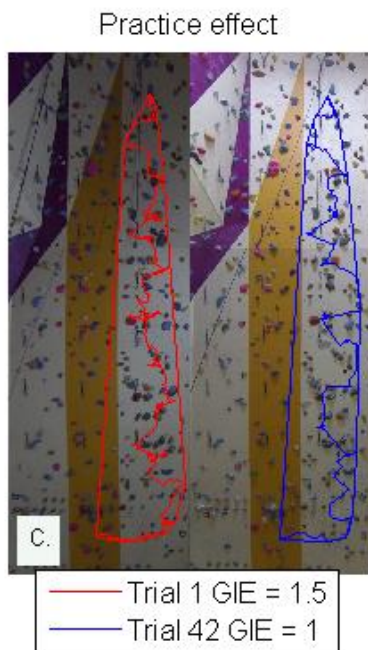
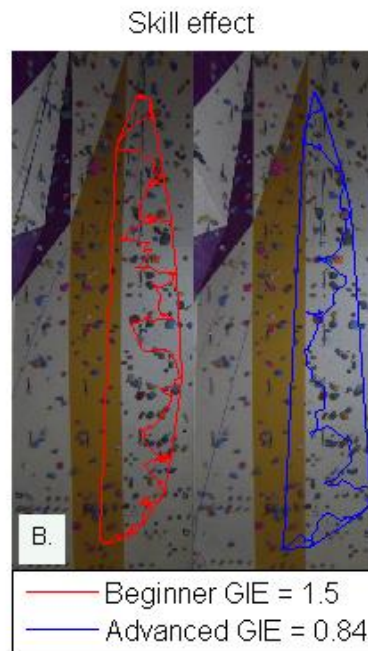
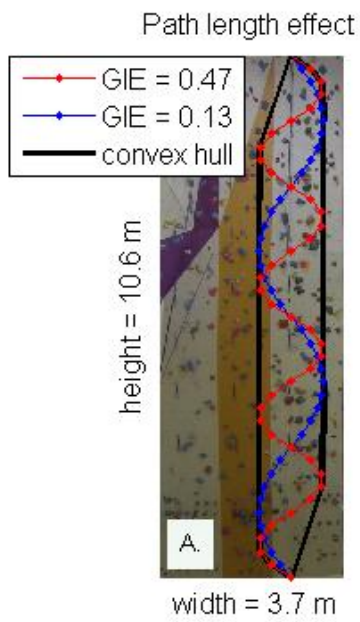
Thank you for your comments regarding the GIE as a representative entropy measure. It should be said that the GIE was introduced as a measure of spatial complexity following Cordier and colleagues [1-4] and has since been adapted to investigate skill [4, 5], practice [4] and route design [6] effects. To be clear, your concerns have been discussed elsewhere and for a full theoretical treatment I refer you to Cordier's 1994 and 1996 papers, both, published in Human Movement Science [1, 4] (and see also [3]). Aside from its theoretical consistency, a main interest of adapting GIE is, that, according to Cordier et al. [4] the GIE can assess the spatial fluency of the climbed trajectory. The higher the entropy value, the higher the irregularity of the climbing trajectory, whereas the lower the entropy value, the more regular is the route trajectory. GIE has a number of advantages over other reported spatial variables (such as the average movement distance [7]) in that it is readily interpreted with respect to climbing activity, accounts for climb height and, shown to be effective for detecting skill [2], practice [2], route [8] and technique effects in climbing tasks [5, 9]. Furthermore, data collection to perform an entropy calculation is relatively straight forward, involving use of a single camera [10]. Figure 1

shows how entropy is calculated (Panel A) and with respect to changing the length of an analysed trajectory. Also shown are skill (Panel B), practice (Panel C) and technique (Panel D) effects. In fact the main interests of using GIE in this study is that it is sensitive to when climbers become blocked at which point they typically begin to search for a route pathway. If this is done inefficiently, a large amount of hip displacement tends to occur, increasing GIE.

To address these concerns, we have updated the introduction to more fully detail the conceptualisation of GIE according to Cordier and colleagues. Thank you concerns regarding relationships between energy and entropy, we have rephrased our conceptualisation (which followed Edelman and Galley) as follows:

“Theoretically, then, measures such as GIE provide an indication of how effectively degeneracy is exploited in managing system stability (e.g., such as to avoid falling during a climbing activity) [3, 11].”





Reviewer #1: The study examines the learning and transfer effects of the climbing tasks for performers of different climbing experiences. The hand-hold orientations were manipulated in practice. All the performers practiced 4 sessions of 3 trials and performed a transfer trial after the last practice session. The exploration behavior (number of touches without actual support) and the Geometric Index of Entropy of the climbing trajectory of the climbers' hips were used as the main dependent variables for analyses. The study suggested that both groups of climbers showed the learning effect on the double-hold route whereas the transfer effect was differentially exhibited in the different dependent variables from different groups of climbing experiences. The main focus of the study was based on the concepts of change of affordance from the ecological psychology perspective and the concept of intrinsic dynamics of the dynamical systems theory. Although the authors designed the experimental conditions accordingly, there are still related issues remained to be addressed.

For the climbing experience, the self-reported F-SRD 6a-6b and 5a-5b need to be described in more detail such as the range of the scale and a general description of the climbing ability.

Agreed, the range and relevant references have been included.

In the discussion, "...The less experienced climbers' transfer of skill to the horizontal route can be explained as a function these grasping opportunities matching fundamentally stable grasping actions, such as ladder climbing "... seems to suggest that these participants had no climbing experience other than the possible ladder climbing experience from the general daily chores. Other statements related to the experience of the participants, such as "... knowledge of the vertically orientated grasping pattern of coordination needs to be acquired through experience", and "... associated with vertically aligned edges during route finding appeared to require experience to stabilize", seem to suggest that the F-SRD 5a-5b had no experience of vertical holds, yet in the description of the route design, all routes used in the experiment were held constant at the level of F-RSD 5b. Is the orientation of the holds a factor considered in the route difficulty? If it is, how is it related to the levels of the two experimental groups? Why the data from the transfer trials were only compared with the first trials in the fall and use of hand hold but not in the entropy and touches? The discussions on the learning effects for the less experienced climbers were specific to the relation between the design of the routes and the level of the climbers, but little has been described about the nature of the skill levels of the two experimental groups.

It is possible that the hold orientations can be interpreted as different levels of relative difficulty, which is a way of interpreting learning effects generally. However, as we state in the manuscript we only controlled for the absolute difficulty of the routes by having multiple route setters arrive at a consensus for absolute difficulty. Rather than focusing on relative difficulty, we focus the discussion on the specific manipulations made in hold design interpreted relative to the reasons there might have underpinned skill effects.

In Line 256, "...more complex route design would increase entropy and hold exploration....more experienced climbers would display lower entropy and hold exploration". How does complexity and difficulty relate to each other? Is there an operational definition of complexity since complexity has

been manipulated in the design of route?

Similar to the point above, we can talk about information similar to how we talk about complexity (and is one of the reasons GIE was used). The use of the complexity both a preference to nature of the manipulations in the hold designs and way use of GIE. The reader is free to interpret these manipulations along the lines of relative difficulty as a matter of theoretical position.

The entropy calculation needs to be explained in more detail. GIE is one of the main variables for analysis; it will be helpful to have an illustration of the actual climbing "path" and the perimeter of the convex hull around the "path" for many readers who do not have an intuitive idea of the measure.

To be clear, your concerns have been discussed elsewhere and for a full theoretical treatment I refer you to Cordier's 1994 and 1996 papers [1, 4] (and see also [3]). The main interest of adapting GIE is, that, according to Cordier et al. [4] the GIE can assess the spatial fluency of the climbed trajectory. The updated, more explicit description for of the computation is given as follows:

**"Geometric index of entropy.** More formally, the GIE is a ratio of the path length of a trajectory to the perimeter of its convex hull [4] and is a uniquely spatial indicator of performance. GIE is given for a given trajectory  $x : [0, T] \rightarrow R^3$ , letting  $\Delta x$  be the trajectory length:

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

and  $\Delta c(x)$  the convex hull perimeter.

The GIE is then given by:

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

noting that the division by  $\log(2)$  places the GIE in dimensionless terms (bits) ."

In order to address the concern regarding visualization we have referred readers to Sibella et al., (2007) who has already exemplified this nicely.

For the statistical analyses, the intuitive impression from figure 3 does not suggest a normal distribution from the exploration data. Did the exploration data fulfilled the normal distribution requirement for F/t tests ?

These data were omitted to keep the stats write-up as brief as possible. As stated in the methods, tests for sphericity were carried out and fulfilled assumptions.

Below is the SPSS output for Mauchly's test on the exploratory actions data set:

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.
Route	,760	3,019	2	,221
Practice	,394	9,974	5	,077
Route * Practice	,107	21,883	20	,373

It is also worth noting that all follow up comparisons were carried out with Bonferroni adjustments to the p values (stated in text and the table captions).

As for the non-parametric tests, it was not clear either in method or in results that how the tests were conducted (within the group among the sessions/routes, between groups). There was no report on the Friedman test result.

For the non-parametric tests, we have provided clarifying details to indicate practice and route comparisons.

In Line 534, a statement of exposure to variability during practice supported the transfer effect was not founded. There was no control condition to contrast the variable practice condition to make such conclusion.

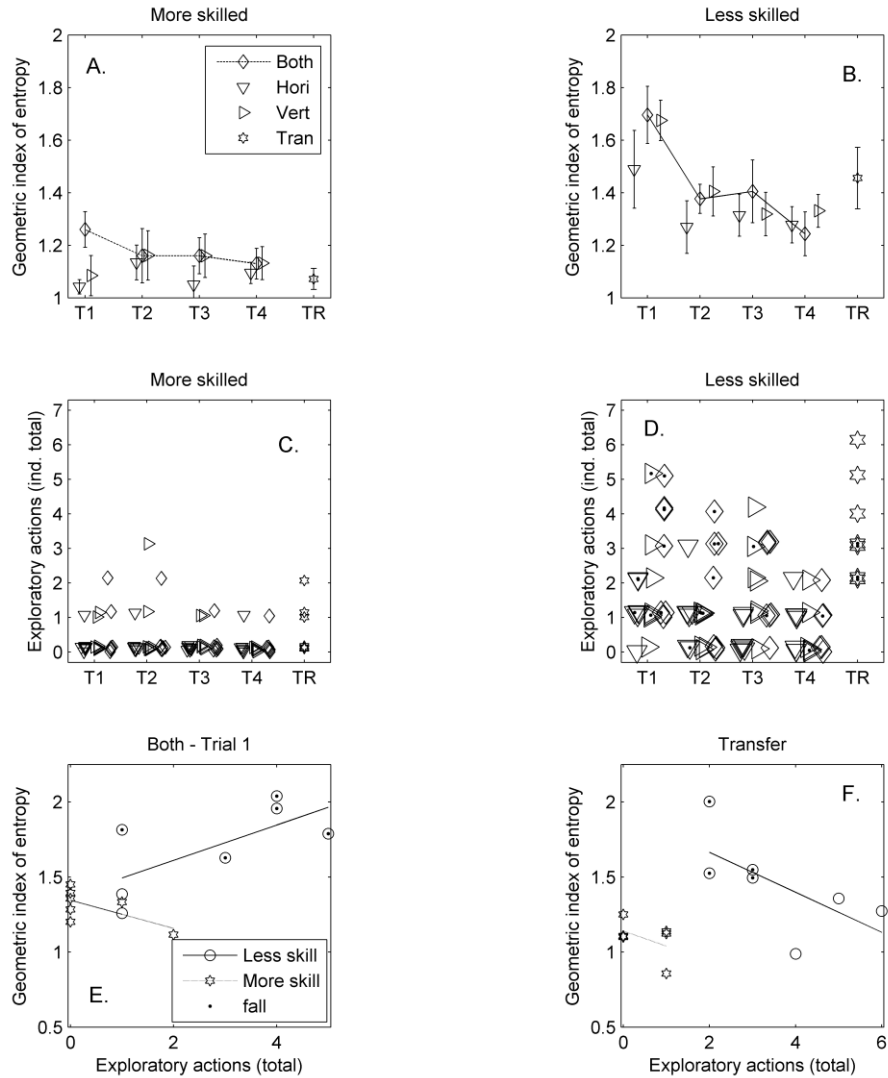
Agreed, we adjusted the interpretation accordingly and tempered the discussion including the statement that:

“future research should consider implementing an independent group design in order to determine if a specific condition underpinned the transfer effects. For instance it may be for the less experienced climbers either the double edged or vertical edged route could have driven the transfer effect.”

Is there a relation between the two main variables analyzed? When the exploration remain unchanged over the practice sessions for the more experienced climbers, what would be the cause of the reduction of the entropy (complexity) measure?

Agreed, we have discussed this possibility as potentially being driven at the visual level. Typically a reduction in entropy indicates that climbers has adapted an efficient route pathway. A possible candidate is that hand hold exploration is induced either as an inability to determine how to grasp or use holds in the less experienced climbers. Additionally, there is the possibility these data are correlated (and is a point of discussion). Indeed, important relationships seemed to

occur in the first trial of practice, and in the transfer test in the less experienced group (see graphs E and F):



These concerns are discussed in text.

Minor points

L168 Was the counter balance procedure performed among participants or within participant among sessions?

Yes, among participants, so that the order to treatment from one session to the next was diversified across participants. Updated in text.

L175 Is the luminous marker the LED mentioned in L191?

Yes, clarified in text.

L191 Need to define the position of hip

Clarified in text.

L198 The GIE formula, the "2" after Log sign a multiplier or a base for the logarithm? Since there were a couple of equations in the manuscript, numbering the equations is recommended

Clarified in text (see above the response to the major comment).

L251 The effect size equation, parenthesis should be added for the denominator  
Results The terminology used in the results (including the figure labels and captions) need to be consistent. (Route/condition, practice/trial)

Thank you, in fact we've chosen to remove the equation and instead provided a reference for the interested reader.

Agreed, the graphs have been updated.

L286 Check the DoF in  $F(1, 12) = 2.274$  for the route x practice interaction

Thank you updated.

A 3-way mixed design ANOVA was indicated in the data analysis section, was there a 3-way interaction effect ?

No the 3-way tests were not significant. However, we followed up significant main and interaction effects.

L339 "10 falls at trial 1 (from a possible 21 total)" Was the possible total trial only regard one group?

Here we are dealing here with the group effect (includes all conditions).

L340 trial "4" instead of trial 1

Thank you updated

L348 missing b)

Thank you updated

L353 the amount "of"

updated

L412-414 ".....less chaotic route finding....", it is not clear what does the word "chaotic" mean here. Suggest to elaborate or rephrase it.

Rephrased to: 'in terms of improved fluency at the hip'

L460 "It was be expected " →It would be expected...

Rephrased

L463 overly "emphasis" → emphasise

Updated

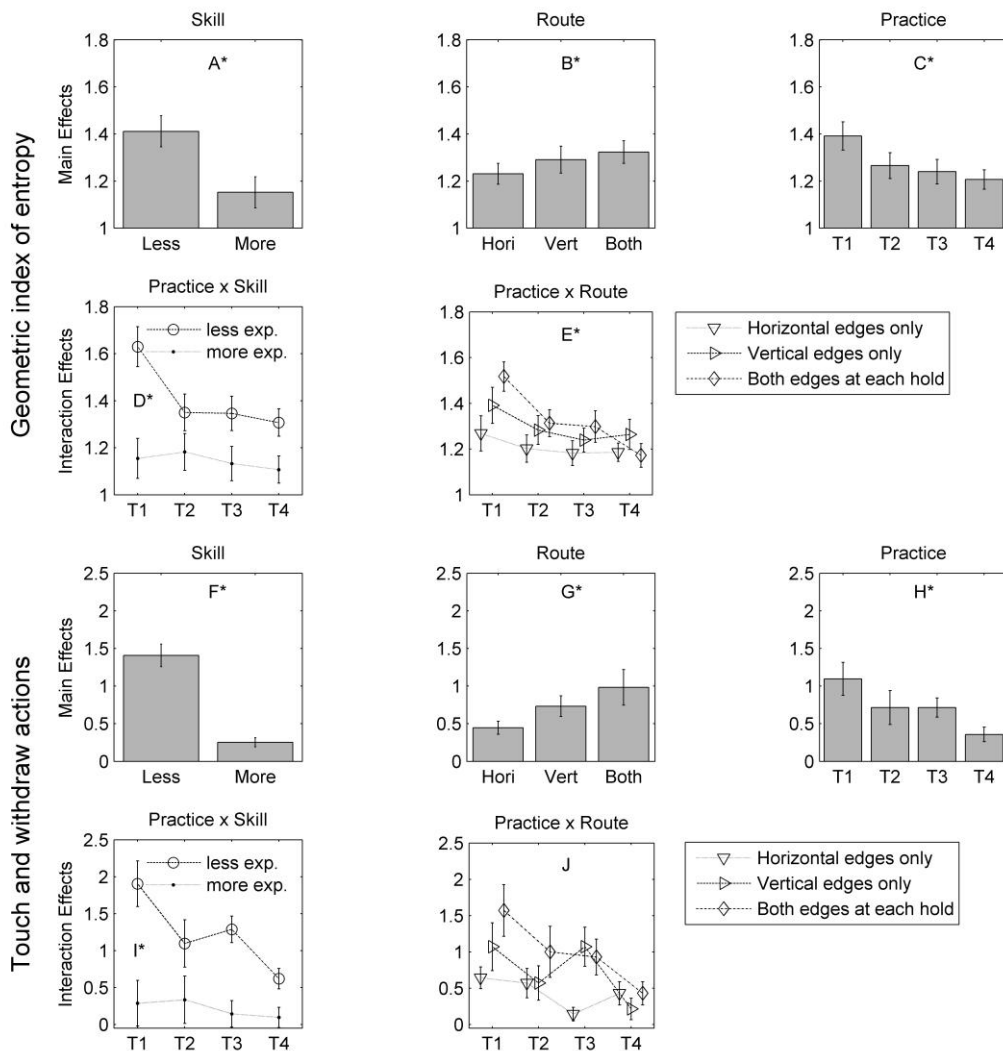
Figure 2 Since the interaction effects were the main focus, the 6 panels that show the 3 main effects may be taken away; the 3 main effects did not present meaningful information. The units of the vertical axes were missing. In caption, Graph E and "H" should be "J", check the DoF of the interaction of route and practice session.

Thank you, with regard to the taking out the main effects, although we were interested in the interaction effects, we feel the main effects provide a complete picture and we prefer to include these.

The vertical axis were provide to the left, we have updated the figure to clarify.

We have carefully examined the figure:

Learning phase: Main effects & Interactions (Error bars = SEM)



Reviewer #2: I had the opportunity to review the manuscript (ms) entitled 'Constraints representing a meta-stable regime facilitate exploration during practice and transfer of learning in a complex multi-articular task' submitted to Human Movement Science (HMS).

I actually found the present ms very well written and structured, as well as clear and precise. Overall, I think that the aims of the ms are clearly defined and followed; that the findings are well organised, and follow the hypotheses developed within the Introduction; and that the conclusions are justified by the findings. The illustrations (Figures, Tables and pictures of the holds) are both necessary and adequate. Lastly, the references are adequate - though I suggest the authors to consider, if they find it of interest when discussing their findings, a couple of publications in the field of sport climbing that used similar methods (e.g., behavioural data) and examined some of the aspects discussed (e.g., route previewing;



visuo-motor aspects).

(1) Would it be interesting to compare entropy values from other studies at all? I fully appreciate that the routes climbed elsewhere will have been different than the routes climbed in the present study but I wonder whether it would be of any use to compare, at least, the range of differences in entropy values between groups/levels across different studies to discuss some of the findings here. For instance, were the differences here as large as the differences in other studies (again, even though the conditions may have been different and the routes obviously were different). Just food for thought that a leave to the authors with.

Agreed, we have included a reference to a recent review providing more detail on entropy outcomes.

(2) Unless otherwise mistaken, I do not recall to have seen any indication that climbers did fall. I wonder whether this is the case. If they did fall-off, I wonder whether there could be further information given as to how that was dealt with (e.g., procedures, entropy measures). If they did not fall-off, which it may be the case given that the routes designed matched lowest climbing level of participants, may be it could be said - if this is the case and I missed it out, I do apologise in advance.

Yes, these were detailed in the results section. One of the reasons we used GIE is that it is dimensionless (units are in bits), since we divide the trajectory length into the convex hull. In fact often prior to a fall individuals will extensively explore at the hip, leading to an increase in the GIE regardless of the absolute height to which they climb. Regarding the ability levels of the participants, we have discussed limitations in using the F-RSD approach. One possibility for future research is to consider adopting scanning procedures prior to recruiting participants.

(3) L62-65. Is it necessary to provide so many references here? Would not a couple do, may be preceded by e.g.?

Agreed, updated.

(4) L158-60: Is there any rationale other than having equal numbers in both groups? I think it would have been better to divide participants into groups based on some climbing performance rationale or parameter, though I appreciate that (a) it may have been difficult to find participants given the research design adopted, and (b) at the end of the day, there are two different levels - though one could argue that 5c and 6a there may not differ that much (unless rationale provided...?!). Previous research has provided some kind of rationale to clarify group classification or explain participant level (e.g., Sanchez et al., 2010, 2012).

Agreed. It should also be noted that their training history differed significantly we have update the rationale following Newell:

“With respect to the intervention routes, this group might be considered as corresponding to a coordination stage of learning [12].... These participants [the more skilled group] reported roughly 3 years of climbing experience and might be considered at a control stage of learning with respect to the intervention routes.”

(5) L164: Could the authors provide a range, as it is not clear to me how long may have the testing taken? Unless I am mistaken, 'four separate days with at least two days separating each session' could be anything; that is, one climber could have been tested over a week while another climber could have been tested over a month...

Agreed, updated (the experiment was run over two weeks).

(5) L183 - Behavioural data: A couple of studies in sport climbing that the authors may find of interest to discuss some of the points they address in their Discussion had adopted similar methods too. Indeed, the authors may find of interest Sanchez and Dauby (2009) study in climbing and imagery and video-modelling (visuo-motor aspects) to discuss further 'number of actions available - functional learning strategy - vs more exploratory behaviours - descriptive learning strategy'). Similarly, the work in 'route previewing' (Sanchez et al., 2012) may be of interest to discuss route knowledge and route finding, a similar - though not exactly - mechanism/skill in sport climbing.

#### References.

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, 356-363.

Sanchez, X., & Dauby, N. (2009). Imagery and videomodelling in sport climbing. *Canadian Journal of Behavioural Science*, 41, 93-101.

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

Thank you, updated, agreed these studies support key points in the methods and discussion.

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1. Cordier, P., G. Dietrich, and J. Pailhous, *Harmonic analysis of a complex motor behavior*. *Human Movement Science*, 1996. **15**(6): p. 789-807.
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11. Edelman, G.M. and J.A. Gally, *Degeneracy and complexity in biological systems*. Proceedings of the National Academy of Sciences, 2001. **98**(24): p. 13763-13768.
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## Tables

**Table 1**

Table 1. Follow-up of the learning effect across each route for each group on entropy and hand hold exploration

Variable	Group by condition		Trial 1		Trial 2		Trial 3		Trial 4		ANOVA-RM
	More Exp		Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Entropy	Horizontal		1.04	0.07	1.14	0.18	1.05	0.19	1.10	0.11	F(3, 18) = 1.347, p =.291
	Vertical		1.08	0.20	1.16	0.25	1.16	0.22	1.13	0.17	F(3, 18) = 0.987, p =.421
	Both*		1.26 <sup>^</sup>	0.11	1.16	0.12	1.13	0.13	1.05	0.09	F(3, 18) = 6.258, p =.004
<b>Less Exp</b>											
Entropy	Horizontal		1.50	0.40	1.27	0.27	1.31	0.21	1.28	0.18	F(3, 18) = 1.574, p =.230
	Vertical*		1.70 <sup>^</sup>	0.37	1.41	0.22	1.32	0.17	1.40	0.31	F(3, 18) = 6.552, p =.003
	Both*		1.70 <sup>^</sup>	0.29	1.38	0.15	1.41	0.32	1.25	0.23	F(3, 18) = 5.820, p =.006
<b>Touches</b>											
Touches	More Exp										
	Horizontal		0.14	0.38	0.14	0.38	0	0	0.14	0.38	F(3, 18) = 0.391, p =.761
	Vertical		0.29	0.49	0.57	1.13	0.29	0.49	0	0	F(3, 18) = 1.079, p =.383
Both		0.43	0.79	0.29	0.76	0.14	0.38	0.14	0.38	F(3, 18) = 0.344, p	

=.794

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<b>Less Exp</b>									
<i>Horizontal</i>	1.14	0.69	1	1	0.29	0.49	0.71	0.76	F(3, 18) = 1.895, p =.167
<i>Vertical</i>	1.86	1.68	0.57	0.54	1.86	1.35	0.43	0.79	F(3, 18) = 3.138, p =.051
<i>Both*</i>	2.71 <sup>^</sup>	1.70	1.71	1.70	1.71	1.25	0.71	0.76	F(3, 18) = 7.000, p =.003

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\*significant effect accounting for the six comparisons per outcome variable (required alpha level set at 0.006); <sup>^</sup>Contrast relative to Trial 4 for the same condition was significant

**Exp** = experience; **RM** = repeated measures

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**Table 2**

**Table 2.** T-test omnibus of between group and within the group effects on entropy and hand hold exploration between trial 4 of the double edged route and the transfer route.

Variable	Group	Double-edge route (T4)		Transfer route		Paired t-tests (2-tailed)
		Mean	SD	Mean	SD	
<b>Entropy</b>	<b>More Exp</b>	1.096	.155	1.185	.315	1.222(6) p = .27
	<b>Less Exp</b>	1.248	.226	1.456	.310	2.243 (6) p = .07
Independent t-tests (2-tailed)		1.45(12), p = .17		1.62(12), p = .13		
<b>Touches</b>	<b>More Exp</b>	0.143	.378	0.714	1.512	2.828(6) p = .03
	<b>Less Exp</b>	0.714	.756	3.571	.756	4.804(6) p = .003*, r = .89^
Independent t-tests (2-tailed)		1.79(12), p = .10		4.47(12), p = .001*, r = .79^		

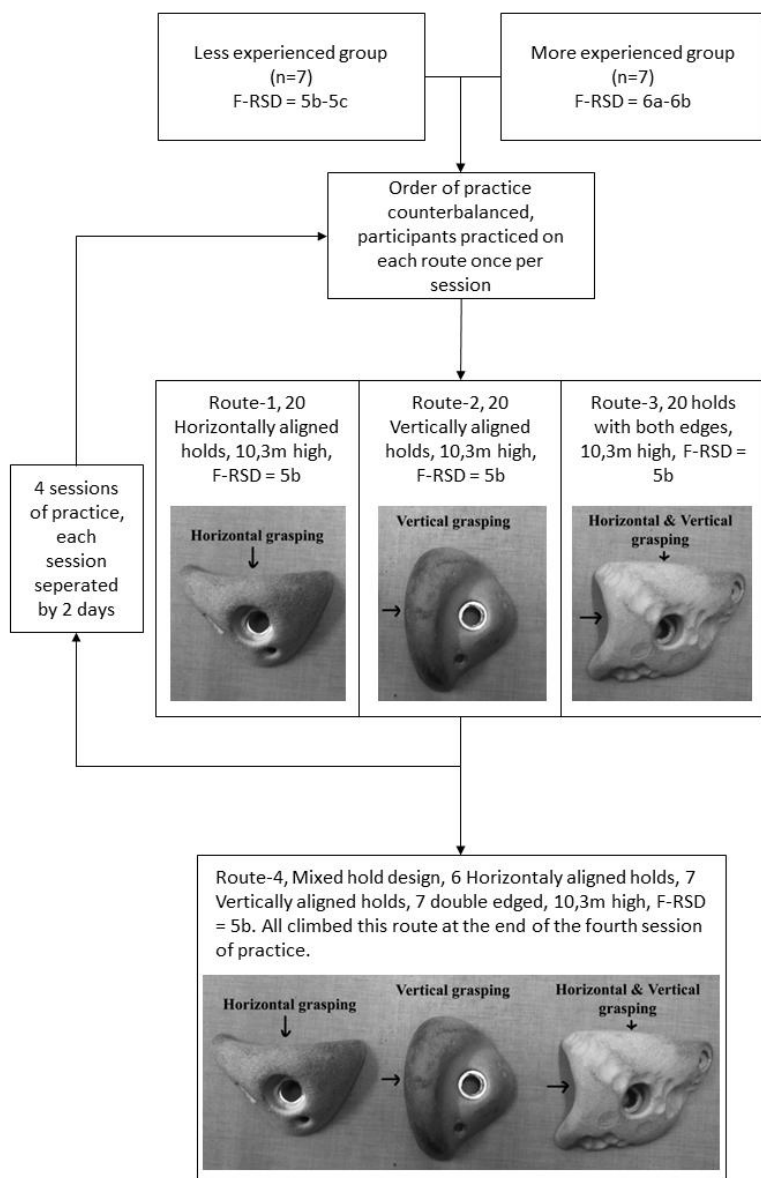
\*Significance adjusted for the eight comparisons (required alpha level set at 0.006)

$$^{\wedge}r = \sqrt{(t^2/t^2+df)}$$

**Exp** = experience

## Figures

Figure 1

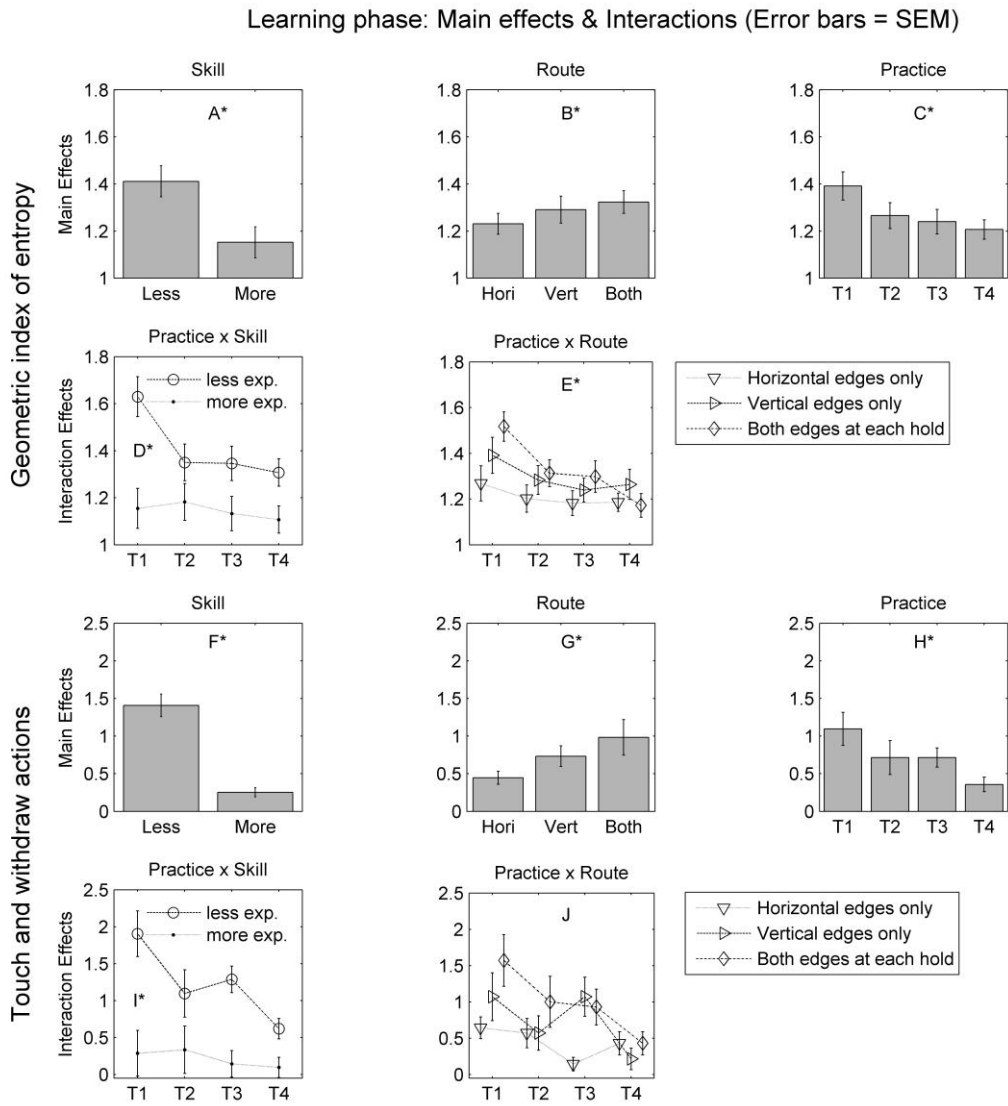


**Figure 1.** Orientation and shape of the holds for the experimental routes. The arrow indicates the grasping edge offered by the hold design. Route-1 was designed using holds graspable with an overhand grip (knuckles running parallel to the ground). Route-2 was

designed using holds graspable along the vertically aligned surface (knuckles running perpendicular to the ground). Route-3 was designed using holds that each were graspable horizontally and vertically. The transfer test included all three types of holds.



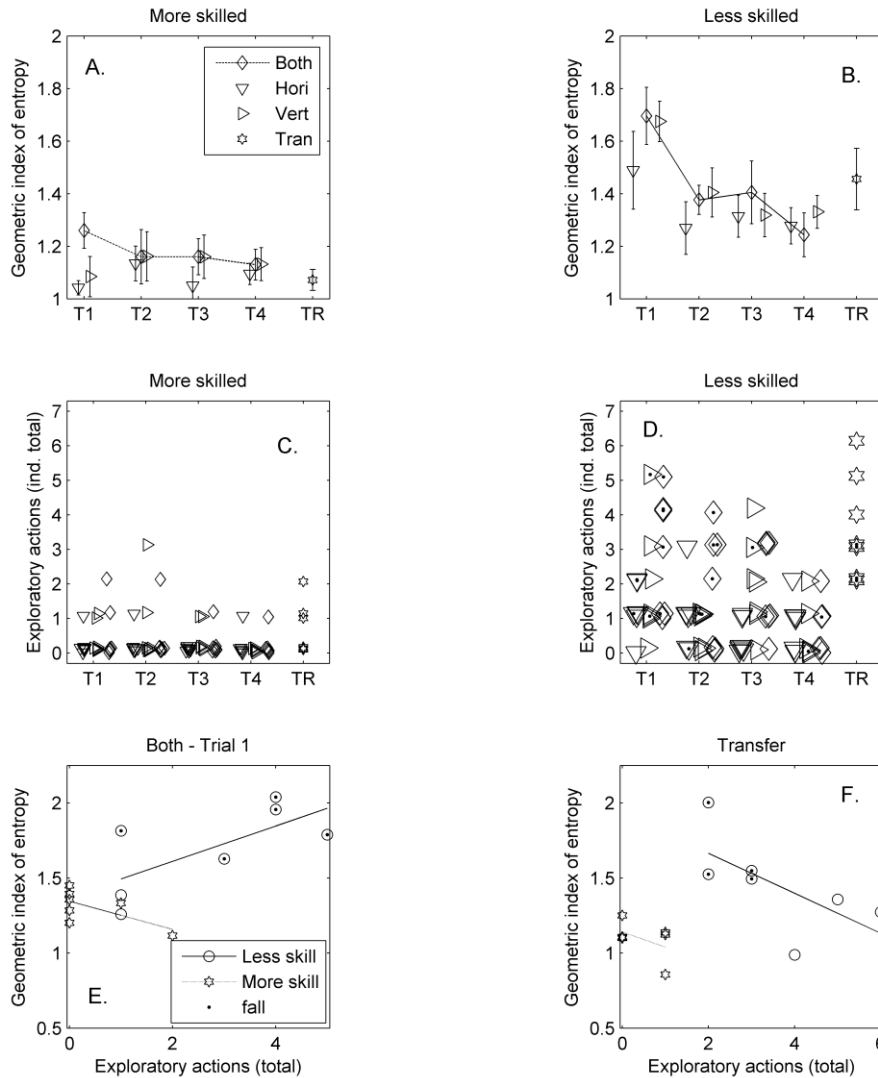
**Figure 2**



**Figure 2.** The main and interaction effects across the two main dependent variables, entropy (Graphs A-E) and hold exploration (Graphs F-J). **Note:** **Both** = Double edged route; **exp.** = experience; **Hori** = Horizontal route; **SEM** = standard error of the mean; **T** = Trial; **Vert** = Vertical route; \* = significant main or interaction effect.



**Figure 3**



**Figure 3.** The entropy and hand hold exploration across each condition, over practice and under transfer for the more experienced group (Graph A and C) and the less experienced group (Graph B and D). Also indicated are instances of falls (filled in shapes in figure D). Graphs E and F highlight the change in relationship between exploration and entropy in trial 1 of the double edged route and the transfer test. **Note:** **Hori** = Horizontal route; **SEM** = standard error of the mean; **Tran** = Transfer route; **T** = trial; **Vert** = Vertical edged route.

