



17 **Abstract**

18 Understanding the evolution of human technology is key to solving the mystery of our  
19 origins. Current theories propose that technology evolved through the accumulation of  
20 modifications that were mostly transmitted between individuals by blind copying and the  
21 selective retention of advantageous variations. An alternative account is that high-fidelity  
22 transmission in the context of cumulative technological culture is supported by technical  
23 reasoning, which is a reconstruction mechanism that allows individuals to converge to  
24 optimal solutions. We tested these two competing hypotheses with a micro-society  
25 experiment, in which participants had to optimize a physical system in partial- and degraded-  
26 information transmission conditions. Our results indicated an improvement of the system over  
27 generations, which was accompanied by an increased understanding of it. The solutions  
28 produced tended to progressively converge over generations. These findings show that  
29 technical reasoning can bolster high-fidelity transmission through convergent transformations,  
30 which highlights its role in the cultural evolution of technology.

31

## 32 **Introduction**

33       Today technology pervades human life, and it is often taken for granted that technology  
34 and science progressively become more advanced and more refined through time. Yet, the  
35 origin of this capacity remains a fascinating mystery. Other primates sometimes use tools  
36 [e.g., chimpanzees (1), capuchins (2), orangutans (3)] and have sometimes been shown to be  
37 doing so for very long periods of time (4). There is also evidence that, like humans, non-  
38 human primates learn to use tools through social learning, by the observation of tool-using  
39 conspecifics (5). However, human technology is strikingly different because non-human  
40 primate tool use does not evolve and does not gradually become more efficient and more  
41 complex through time (6). The term Cumulative Technological Culture (CTC) has been  
42 coined to refer to the progressive increase in the complexity and/or efficiency of tools and  
43 techniques that are too complex to be invented by a single individual (7–9). Interestingly,  
44 there is increasing evidence that some non-technological aspects of animal culture can  
45 cumulatively evolve (10–12), raising the question of how and why technology became  
46 cumulative in humans and not in other primates.

47       CTC has been considered to be driven by two engines: High-fidelity transmission, the  
48 similarity between tools and techniques across episodes of transmission [also called *episodic*  
49 *fidelity*, see (13)], and innovation (14). The crucial role of high-fidelity transmission in CTC  
50 has been repeatedly stressed with the rationale that, when an innovation appears, it will  
51 quickly be lost if it cannot be faithfully transmitted to others (7, 15–19). High-fidelity-  
52 transmission has often been assumed to result from unique social-cognitive skills that allow  
53 humans to imitate or “infocopy” [(6, 18, 20, 21); also called high-fidelity copying or  
54 *propensity fidelity*, see (13)]. Following this view, the role of causal reasoning in CTC has  
55 often been minimized by assuming that complex technologies result from the accumulation of  
56 many often poorly understood improvements made over generations (7, 22, 23) combined

57 with rare intentional improvements achieved through causal reasoning (24). Although the  
58 term *causal reasoning* is widely employed in the literature, we have stressed (25) that the  
59 term *technical reasoning* may be more appropriate in the field of CTC because it refers to a  
60 specific form of causal – and analogical – reasoning directed toward the physical world. Thus,  
61 the term technical reasoning will be hereafter used to refer to this specific kind of reasoning.

62       Importantly, the similarity observed between tools or techniques in CTC needs not  
63 come from the existence of copying mechanisms (26, 27). An alternative explanation, the  
64 cultural attraction theory (26, 28, 29), is that humans are endowed with cognitive mechanisms  
65 that are not specifically designed for copying but that transform and adapt what is socially  
66 learned to the ends and characteristics of the learning individual. Under such a view, high-  
67 fidelity transmission is achieved through convergent transformations, that is, individuals with  
68 the same goal will give rise to similar cultural products through shared cognitive skills, goals,  
69 and environments (30, 31). This view has recently received support from theoretical,  
70 experimental, and field studies on cultural evolution in humans (32–37) and non-human  
71 primates (31, 38) and is also in line with studies on language evolution (39). For instance,  
72 arguments transmitted along transmission chains could become degraded and then fully  
73 reconstructed through deductive reasoning (40). With respect to CTC, the cultural attraction  
74 theory translates into the fact that individuals use technical-reasoning skills to solve complex  
75 technological problems and that high-fidelity transmission is the result of convergent  
76 transformations.

77       To experimentally examine the role of convergent transformations *versus* copying  
78 mechanisms in CTC, we used a recently developed task that was aimed at providing the sort  
79 of complexity encountered in CTC. Derex et al. (22) reported a micro-society study designed  
80 to investigate the role of causal understanding in CTC. The task consisted of optimizing a  
81 wheel system (**Fig. 1A**). This task was multidimensional because the speed of the wheel

82 depended on its moment of inertia (i.e., a wheel with its four weights close to its center is  
83 faster than a wheel with its four weights farther from the center) and the position of its center  
84 of mass (i.e., the initial acceleration is better when the wheel is unbalanced with the center of  
85 the mass located ahead and above the axis of the wheel; **fig. S1**). The participants performed  
86 the task as members of chains of five participants (**Fig. 1B**). The experimenter transmitted to  
87 each participant (except those of the first generation) the weight configurations and their  
88 associated speeds from the last two trials of the previous participant (hereafter called  
89 Configurations+Speed condition). Participants' understanding of the wheel system was  
90 assessed with an understanding test consisting of selecting the fastest wheel configuration out  
91 of several presented. The results indicated that the wheel system became progressively  
92 optimized, and although Derex et al. (22) found no improvement in understanding, we  
93 performed a partial replication (41) motivated by some methodological issues and  
94 demonstrated that the improvement was linked to the participants' understanding of the  
95 technology (i.e., their understanding increased through time, they were able to transfer this  
96 understanding to other problems, and they were better than controls).

97 The findings reported in both Derex et al. (22) and our prior study (41) gave limited  
98 insight into the process through which participants arrived at better configurations because the  
99 participants had access to all the information they needed (wheel configurations and  
100 associated speeds) to reproduce with high fidelity the wheel systems produced by their  
101 predecessors. Nevertheless, our findings (41) indicated that even when individuals had access  
102 to all the information needed to blindly copy, they formed a causal representation of the  
103 physical system that they used to produce improvements. The role of technical reasoning may  
104 appear redundant here but could reveal its full potential if the information transmitted  
105 between individuals is incomplete or incorrect (25). Partial information combined with  
106 technical-reasoning skills might allow an individual to converge toward the same technical

107 solution or another technical solution that maintains – or even improves – the technology  
108 (25).

109 The present study aimed to test this possibility through two micro-society conditions, in  
110 which participants had five trials to improve a wheel system, as described above (14 chains of  
111 five participants in each condition; **Fig. 1, A and B**). After their five trials, the participants’  
112 understanding of the physical system was assessed with an understanding test (twelve items  
113 for center of mass and twelve for inertia). In the Speed-Only condition, the only information  
114 that was transmitted to the next participant was the last two wheel speeds of the previous  
115 participant in the chain (i.e., no information at all about the configurations associated; **Fig.**  
116 **1C**). In the Configurations+Speed+Noise condition, the participants were given two weight  
117 configurations and their associated speeds. The configurations came from the previous  
118 participant in the chain but were modified by randomly changing the position of the four  
119 weights closer to or further from the center of the wheel (**Fig. 1C**). Therefore, the participants  
120 had access to partial or degraded information in both conditions. If copying is crucial for CTC  
121 and technical reasoning is non-necessary, no improvement of the physical system should be  
122 observed in both conditions, nor should an increase in understanding be found. By contrast, if  
123 technical reasoning is important for completing partial or biased information, then an  
124 improvement of the physical system should be observed in both conditions, and it should be  
125 accompanied by an increase in understanding.

## 126 **Results and Discussion**

127 The results supported the second prediction. The wheel speed increased over  
128 generations in both the Speed-Only condition [Generation estimate, 3.03 m h<sup>-1</sup>; 95%  
129 Confidence Interval (CI): 1.28 to 4.73] and the Configurations+Speed+Noise condition  
130 (Generation estimate, 1.77 m h<sup>-1</sup>; 95% CI: 0.53 to 2.96; **Fig. 2A, fig. S2**) in parallel to the  
131 participants’ total understanding score (Speed-Only: Generation estimate, 2.04; 95% CI: 0.35

132 to 3.88; Configurations+Speed+Noise: Generation estimate, 1.85; 95% CI: 0.40 to 3.05; **Fig.**  
133 **2B**). A link was also found in both conditions between the wheel speed (the best speed of the  
134 last two trials) and the total understanding score (Speed-Only: Wheel-speed estimate, 0.55;  
135 95% CI: 0.39 to 0.73; Configurations+Speed+Noise: Wheel-speed estimate, 0.65; 95% CI:  
136 0.46 to 0.84; **Fig. 3B**). To examine convergence, we computed an intra-generation similarity  
137 score, which reflected the similarity between the wheel configurations of the participants of  
138 the same generation. We found that this intra-generation similarity score increased over  
139 generations within both conditions but not between conditions (Speed-Only: Generation  
140 estimate, 1.41; 95% CI: 0.72 to 2.10; Configurations+Speed+Noise: Generation estimate,  
141 1.75; 95% CI: 1.25 to 2.18; Between: Generation estimate, 0.67; 95% CI: -0.14 to 1.36; **Fig.**  
142 **3C**). Taken together, these results indicate that high-fidelity transmission can arise through an  
143 increased understanding of the task that allow individuals to converge to optimal solutions  
144 [for similar results in a Configurations+Speed condition, see (41); see also **fig. S3**].

145 A careful examination of the evolution of wheel speed over the 25 trials (**Fig. 2A**)  
146 provides additional information about the dynamics of the cognitive processes involved in  
147 each condition. In the Configurations+Speed+Noise condition, the participants in the second-  
148 to-fifth generations maintained the wheel speed from their first trials at the same level as that  
149 of the last trials of their predecessors. This pattern, which is similar to that of the  
150 Configurations+Speed condition of Osieurak et al. [(41); **fig. S4**; see also (22)], suggests that  
151 the participants tended to use – but also to be canalized by [(22, 41) see also (42–44)] – social  
152 information to begin to form a causal representation of what could be an effective physical  
153 system. The early impact of social information on the formation of this causal representation  
154 is confirmed by the presence of a link between the total understanding score and the wheel  
155 speed (the best speed of the first two trials; Wheel-speed estimate, 0.25; 95% CI: 0.01 to 0.45;  
156 **Fig. 3A**).

157 By contrast, as shown in **Fig. 2A**, the participants in the Speed-Only condition seemed  
158 to reinvent the wheel at each generation, with the participants in the second-to-fifth  
159 generations obtaining a very low performance in their first trial, close to that of the first trial  
160 of participants in the first generation. Nevertheless, over their five trials, the participants in  
161 the second-to-fifth generations tended to improve the physical system systematically and  
162 progressively, leading them to outperform their predecessors. This outcome suggests that the  
163 participants in this condition benefited from the social information provided by the speed of  
164 previous wheels by comparing it with the performance based on their initial causal  
165 representation of the wheel system. Thus, the greater the gap between the performance of  
166 their predecessor and their initial performance, the more the participants attempted to modify  
167 – and thus enhance – their causal representation of the physical system, thereby allowing  
168 them to improve dramatically their wheel system over their own trials. Support for this  
169 interpretation comes from the absence of a link in this condition between the total  
170 understanding score and the wheel speed, when the best speed of the first two trials is  
171 considered (Wheel-speed estimate, 0.16; 95% CI: -0.05 to 0.36; **Fig. 3A**).

172 The inertia dimension had a greater impact on the wheel speed than the center of mass  
173 dimension. Therefore, the considerable increase in wheel speed over the five trials implied  
174 that the participants in the Speed-Only condition explored further the inertia dimension and  
175 preferentially enhanced their understanding of this dimension. To investigate this aspect, we  
176 computed two exploration scores, one for the inertia dimension and the other for the center-  
177 of-mass dimension, which reflected the exploration of each dimension over the five trials. We  
178 found that the inertia exploration score increased over generations in the Speed-Only  
179 condition (Generation estimate, 3.63; 95% CI: 1.69 to 5.49; **Fig. 3E**) in parallel with the  
180 participants' inertia understanding score (Generation estimate, 2.28; 95% CI: 0.42 to 4.13;  
181 **Fig. 2D**). In broad terms, the mere availability of information about the predecessor's



182 performance was enough to orient the participants toward a technical-reasoning-based  
183 exploration [reasoned trial and error (25, 45)].

184 The pattern in the Configurations+Speed+Noise condition was different, with no  
185 significant effect of generations on the inertia exploration (Generation estimate, -0.81; 95%  
186 CI: -2.49 to 0.81; **Fig. 3E**) and understanding scores [Generation estimate, 0.26; 95% CI: -  
187 0.98 to 1.56; **Fig. 2D**; for similar results in a Configurations+Speed condition, see (41)]. By  
188 contrast, there was an increase in the participants' center-of-mass understanding score  
189 (Generation estimate, 1.59; 95% CI: 0.79 to 2.50; **Fig. 2C**). This increase was not found in the  
190 Speed-Only condition (Generation estimate, -0.24; 95% CI: -1.18 to 0.75; **Fig. 2C**).  
191 Interestingly, the increase in the center-of-mass score reported in the  
192 Configurations+Speed+Noise condition was accompanied by a decrease in the center-of-mass  
193 exploration score over generations (Generation estimate, -4.88; 95% CI: -8.05 to -1.53; **Fig.**  
194 **3D**). The random noise added before transmission fortuitously and almost systematically led  
195 to the generation of unbalanced wheel configurations (**table S1**), which was critical to observe  
196 the effect of the position of the wheel's center of mass on its speed. Random noise, along with  
197 the canalizing effect associated with the transmission of wheel configurations, seems to have  
198 directed the participants' attention to the center-of-mass dimension, leading them to improve  
199 their understanding of this dimension. These findings highlight how the introduction of  
200 random modifications can favor the understanding of often poorly understood dimensions,  
201 which can in turn lead to specific innovations. The presence of a decrease in the center-of-  
202 mass exploration score suggests that these innovations did not result from lucky errors or  
203 occasional experiments but from the direct contribution of random modifications introduced  
204 along with the canalizing effect. This is telling with respect to our hypotheses because if  
205 participants were using a strategy in which they introduced random modifications and  
206 selected the best outcomes, (1) participants in both conditions would mostly explore the

207 center-of-mass dimension (favored by random modifications) and (2) transmission chains in  
208 the two conditions would converge towards the same outcome (but see **Fig. 3C**).

209 The present study extends previous findings, which have questioned the crucial role of  
210 copying mechanisms (46, 47) and/or emphasized the importance of causal  
211 understanding/inductive biases (48–50) and innovative skills in CTC (51, 52). In this  
212 experiment, participants with very little or randomly transformed social information managed  
213 to improve and converge towards similar outcomes than participants with complete  
214 information [(13, 53) see also (54, 55)]. This is remarkable and demonstrate the importance of  
215 technical reasoning in producing CTC: Technical reasoning is a reconstruction mechanism  
216 that allows us to recover from partial or degraded information obtained through social  
217 learning and therefore guarantees the high-fidelity transmission of advantageous technologies  
218 (i.e., the high similarity between the wheel configurations). Said differently, technical  
219 reasoning can be viewed as a potential cognitive mediator of CTC that allows individuals to  
220 filter information acquired either through their own experience (asocial learning) or through  
221 social learning, by extracting relevant information and rejecting irrelevant information,  
222 irrespective of the origin of this information (25). Technical reasoning might participate in  
223 both the innovative component and the high-fidelity component of CTC, thus implying that  
224 the distinction between these two components might be of convenience rather than of  
225 cognitive distinctness.

226 The use of micro-society paradigms has provided significant insights into the origin of  
227 CTC. As stressed by Miton and Charbonneau (56), participants in micro-society paradigms  
228 “are adept inventors, capable of innovating in a matter of minutes” (p. 4). Consistent with this  
229 fact, our participants were able to improve a multidimensional technology, which is not  
230 obviously intuitive as shown by the results, as well as the understanding of it in only about 20  
231 min and five trials. Showing that technical reasoning can play a reconstruction role in such

232 paradigms can also renew the question of how technologies have evolved in early hominins.  
233 For instance, the Oldowan industrial complex emerged at around 2.6 million years ago. This  
234 industry comprises mainly sharp-edged flakes and the cores from which they were removed  
235 (57). There is no clear tradition within the Oldowan prior to 2 million years ago (58). The  
236 Acheulean industry, which appeared around 1.75 million years ago, corresponds to bifacially  
237 shape stone tools used as handaxes and cleavers. This industry is characterized by a striking  
238 homogeneity, which persisted for around 1.5 million years (59, 60). This shift may reflect the  
239 emergence of high-fidelity transmission in our lineage. Several proposals have been made for  
240 interpreting this shift at a cognitive level, with a particular focus on social cognitive skills (61,  
241 62). The findings reported here provide an alternative interpretation in suggesting that  
242 technical reasoning could have also contributed to the emergence of high-fidelity  
243 transmission. Of course, this interpretation must be taken with caution because other aspects  
244 can also be fundamental to maintain the stability of technologies over long periods of time,  
245 such as the – perhaps presupposed – lesser cost of copying compared to understanding the  
246 technical behavior of conspecifics and the interaction of this learning cost with environmental  
247 conditions (7, 63), the different social-learning strategies [e.g., prestige bias, conformity bias  
248 (20, 64)], or the superiority of some social-learning conditions over others in the transmission  
249 process [e.g., superiority of communication over reverse engineering (65, 66)]. Regardless,  
250 our results show that CTC and the high-fidelity transmission of technology between  
251 individuals should not be systematically interpreted as evidence of cognitive mechanisms  
252 capable of copying coupled to the random retention of useful modifications.

## 253 **Materials and Methods**

### 254 *Ethics*

255 The Ethics Committee of the University of Lyon Department of Psychology approved the  
256 study, and the procedure was carried out in accordance with the ethical standards of the 1964

257 Declaration of Helsinki. Informed consent was obtained from all participants after the nature  
258 and possible consequences of the study were explained [see (41)].

### 259 *Participants*

260 One hundred and forty-six students at the University of Lyon took part in the study ( $M_{\text{age}} =$   
261  $20.84$ ,  $SD_{\text{age}} = 2.91$ ; 102 women). The participants were non-selectively recruited through  
262 advertisements posted on social media websites [see (41)].

### 263 *Experimental apparatus*

264 The wheel system used in the present study was the same as the one used by Osiurak et al.  
265 [(41); for an illustration, see <https://osf.io/m3d7q/>]. A description is provided in **fig. S5**.

### 266 *Procedure*

267 The procedure was basically the same as in (41). The experiment took place in an  
268 experimental room at the University of Lyon (around 30 min in duration). The participants sat  
269 at a table placed 2 m from the experimental apparatus. Before the experiment, the participants  
270 completed a consent form. After the experiment, they indicated whether they had an academic  
271 background in engineering or physics.

### 272 *Experimental design*

273 *Building phase.* This phase was similar in both conditions. Instructions were similar to those  
274 of Osiurak et al. [(41); see <https://osf.io/m3d7q/>]. The participants had five trials to optimize  
275 the speed of a wheel that descended a 1-m-long inclined track. They could move four weights  
276 to any of 12 discrete positions along each spoke and were free to choose their own  
277 configuration (from 1 to 12, with 1 being the closest position to the center of the wheel and 12  
278 the furthest position from the center of the wheel). After the participants used a marker pen to  
279 indicate the positions of the four weights on the wheel (i.e., a paper version of the

280 configuration), the experimenter positioned the weights on the physical wheel accordingly.  
281 The participants were not allowed to move the weights on the physical wheel themselves in  
282 order to prevent damage due to potential repeated awkward manipulations. The wheel also  
283 needed to be placed correctly in its initial position and the release had to be accomplished  
284 without any abrupt movements in order to avoid a modification of the trajectory of the wheel.  
285 Nevertheless, the participants could scrutinize the experimenter moving the weights and  
286 releasing the wheel as well as the wheel descending the track. The time it took the wheel to  
287 travel down the track was automatically recorded by a computer program (see  
288 <https://osf.io/m3d7q/>). The wheel speed and the associated configuration were then displayed  
289 to the participants, who had as much time as they needed to consult their last two  
290 configurations and choose the next one. As explained above, we used a paper-and-pencil  
291 method to display the wheel speeds and the associated configurations (see  
292 <https://osf.io/m3d7q/>). After three trials, the experimenter reminded the participants in the  
293 Speed-Only condition that the wheel speeds of their last two trials would be transmitted to the  
294 next participant in the chain. In the Configurations+Speed+Noise condition, the experimenter  
295 reminded the participants that their last two configurations and the associated speeds would  
296 be transmitted to the next participant in the chain. In this condition, a random noise was  
297 introduced by the experimenter into the wheel configurations before transmission, by moving  
298 the four weights six positions closer to or farther from the center of the wheel (i.e., the  
299 absolute sum of the modifications equaled 6). Thus, if the configuration of the wheel of a  
300 participant on their fourth trial was, for instance, [Position<sub>Top</sub> Weight: 9; Position<sub>Front</sub> Weight: 9;  
301 Position<sub>Bottom</sub> Weight: 5; Position<sub>Back</sub> Weight: 5], a random modification of six positions was  
302 applied (e.g., +1;-3;+2;0), which modified the configuration of the wheel (i.e., Position<sub>Top</sub>  
303 Weight: 9+1=10; Position<sub>Front</sub> Weight: 9-3=6; Position<sub>Bottom</sub> Weight: 5+2=7; Position<sub>Back</sub> Weight:  
304 5+0=5]. The configurations thus modified and their associated speeds were then transmitted

305 by the experimenter to the next participant. The computer program used to generate these  
306 random positions is available at <https://osf.io/m3d7q/>. The introduction of this random noise  
307 frequently generated wheels that did not descend (i.e., speed of 0 m h<sup>-1</sup>). Sometimes, the  
308 program could generate two configurations with null speed for the same participant. To  
309 ensure that the participants in the second-to-fifth generations received at least one  
310 configuration with a wheel that descended, we reran the program until we obtained a wheel  
311 with a non-null speed for the second configuration when the speed associated with the first  
312 configuration was already null. There were 28 chains of five participants each (i.e., 14 chains  
313 in the Speed-Only condition and 14 chains in the Configurations+Speed+Noise).

314 *Testing phase.* In both conditions, the participants completed this phase after the building  
315 phase [see (41)]. They were instructed that they would be presented with items consisting of  
316 four wheels and that they would have to choose which of the four wheels would roll down the  
317 rails faster in their opinion. They could take as much time as they needed to complete the test.  
318 They received no feedback. All the participants saw the same items in the same order. The  
319 understanding test consisted of 24 items (i.e., 12 inertia items and 12 centre of mass items).  
320 The test is available at <https://osf.io/m3d7q/>. Finally, the participants had to write a brief  
321 theory (i.e., less than 340 characters long) about the functioning of the wheel system, which  
322 always started with “The wheel covers the distance faster when...” [for a similar procedure,  
323 see (22)]. The data collected about these theories are not discussed in the present report.

#### 324 *Statistical analyses*

325 One participant in the Speed-Only condition received an incorrect speed from the previous  
326 participant because of an experimental error. The data of this participant were removed, and  
327 the participant was replaced by a new participant. We checked for the presence of outliers for  
328 each condition separately. As our key predictions concerned the increase in wheel speed over

329 generations, we explored whether some chains behaved differently from the others on this  
330 aspect. To do so, we computed the slope associated with each chain with  $x$  being the position  
331 of the participant in the chain and  $y$  the best speed of their last two trials. For each condition,  
332 we obtained 14 slopes. We considered as outliers the chains with a slope that did not fall  
333 within two standard deviations from the mean. This procedure led us to remove one chain of  
334 five participants in the Speed-Only condition, which we replaced with a new chain of five  
335 participants. No chain was removed for the Configurations+Speed+Noise condition. In total,  
336 the data of six participants were excluded, giving us a final sample of 140 participants (14  
337 chains of five participants for each condition).

338 Wheel speed corresponded to the best speed of the first or last two trials. Wheels that did not  
339 travel down were assigned a speed of  $0 \text{ m h}^{-1}$ . To compute the intra-generation similarity  
340 score, we first selected the configuration of the wheel that was fastest among the last two  
341 trials of each participant. Then, for the within-condition similarity score, we compared this  
342 best configuration with the 13 best configurations produced by the other participants of the  
343 same generation, and we did so for each participant of each generation. The comparison was  
344 based on the sum of absolute differences of the positions of the four weights between two  
345 configurations. The positions varied from 1 to 12. Therefore, the maximum absolute  
346 differences could be 44 [i.e.,  $(\text{Position}_{12} - \text{Position}_1) \times 4 \text{ weights}$ ]. The sum of absolute  
347 differences reflected the dissimilarity between the two configurations. Therefore, we  
348 subtracted this sum from 44 to obtain the similarity score. The procedure was the same for the  
349 between-condition similarity score except that we compared the best configuration of each  
350 participant with the 14 best configurations produced by the participants of the same  
351 generation in the other condition. More detail about this intra-generation similarity score is  
352 given at <https://osf.io/m3d7q/> [for a similar procedure, see (67, 68)]. The inertia exploration  
353 score corresponded to the difference between the smallest and the greatest sum of positions of

354 the four weights on the five trials. The greater this difference, the greater the exploration. The  
355 center-of-mass exploration score corresponded to the surface of the convex envelope that  
356 contained the centers-of-mass coordinates of the five wheels. For each wheel, the coordinates  
357 of its center of mass were computed by subtracting the position of the bottom weight from  
358 that of the top weight ( $x$ -coordinate) and the position of the back weight from that of the front  
359 weight ( $y$ -coordinate). The greater this surface, the greater the exploration. More detail about  
360 these two exploration scores is provided at <https://osf.io/m3d7q/>.

361 In both conditions, we first explored the wheel speed over generations. Wheel speed  
362 corresponded here to the best speed of the last two trials. Wheels that did not travel down  
363 were assigned a speed of  $0 \text{ m h}^{-1}$ . We used regression modelling in R [(69); lmerTest package  
364 (70)] to fit a linear model with ‘Wheel speed’ as outcome variable, ‘Generation’ as fixed  
365 effect, and ‘Chain’s identity’ as random effect. The same analyses were conducted for the  
366 understanding scores (Total, Center of Mass, and Inertia), the intra-generation similarity score  
367 (Within-condition and Between-condition), the exploration scores (Center of Mass and  
368 Inertia) and the best speed of the first two trials (Two participants in the Speed-Only  
369 condition and four participants in the Configurations+Speed+Noise condition were excluded  
370 from this analysis because their first two wheels did not descend). We also used regression  
371 modelling in R [(69); lmerTest package (70)] to explore the links between the understanding  
372 scores (Total) and the best speed of the first *or* last two trials. We fitted a linear mixed model  
373 with ‘Understand Score (Total)’ as outcome variable, ‘Wheel speed (the best speed of the first  
374 *or* last two trials)’ as fixed effect, and ‘Generation’ and ‘Chain’s identity’ as random effects.  
375 Statistical significance was set at  $p < .05$  and bootstrapping method was used to estimate 95%  
376 confidence intervals.



377 **References and Notes**

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#### 534 **Competing interests**

535 Authors declare that they have no competing interests.

#### 536 **Data and materials availability**

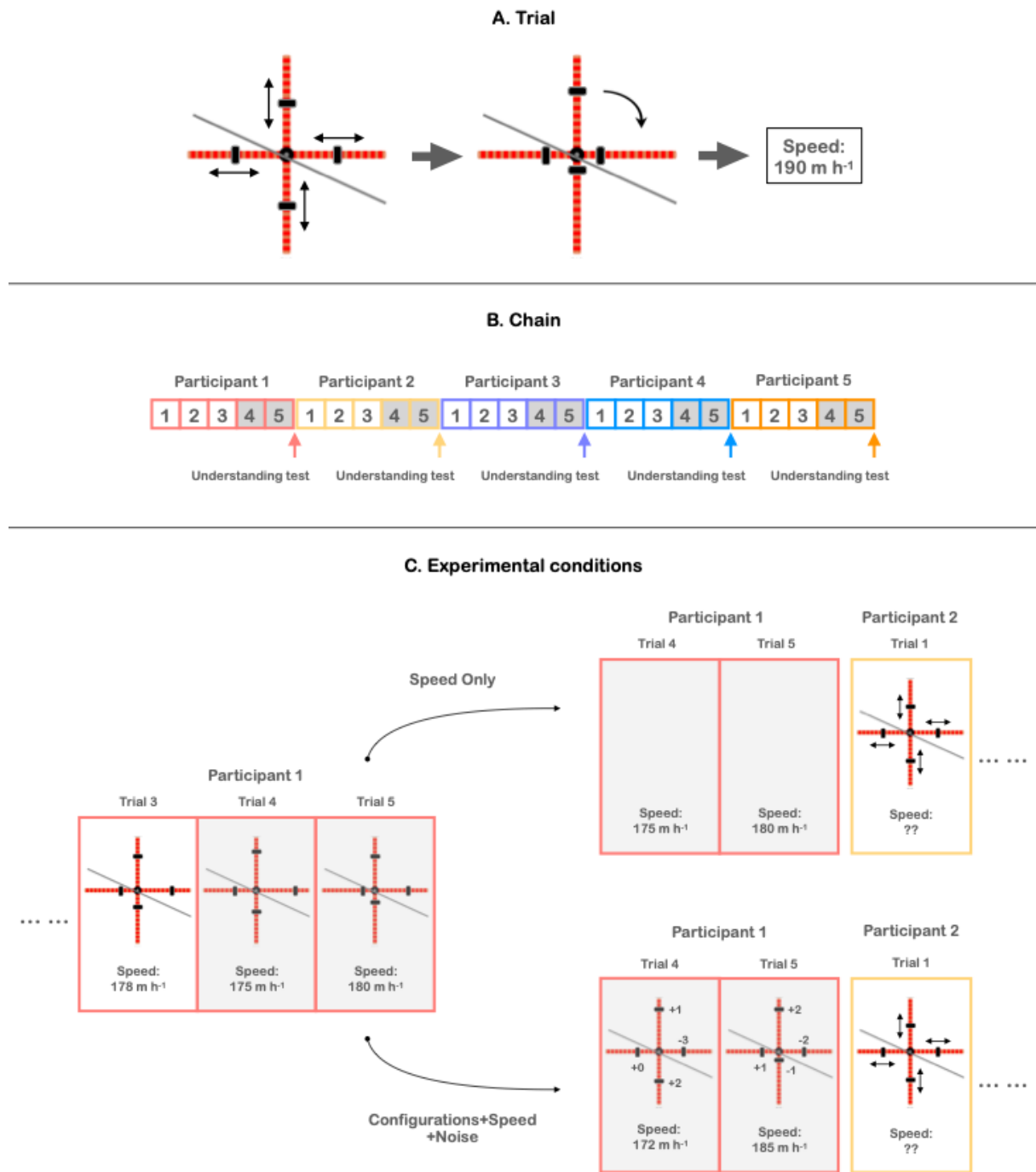
537 The data that support the findings of this study and the codes used in this study are available  
538 at <https://osf.io/m3d7q/>. All data needed to evaluate the conclusions in the paper are present  
539 in the paper and/or the Supplementary Materials.

#### 540 **Supplementary Materials**

541 Figs. S1 to S5

542 Table S1

543

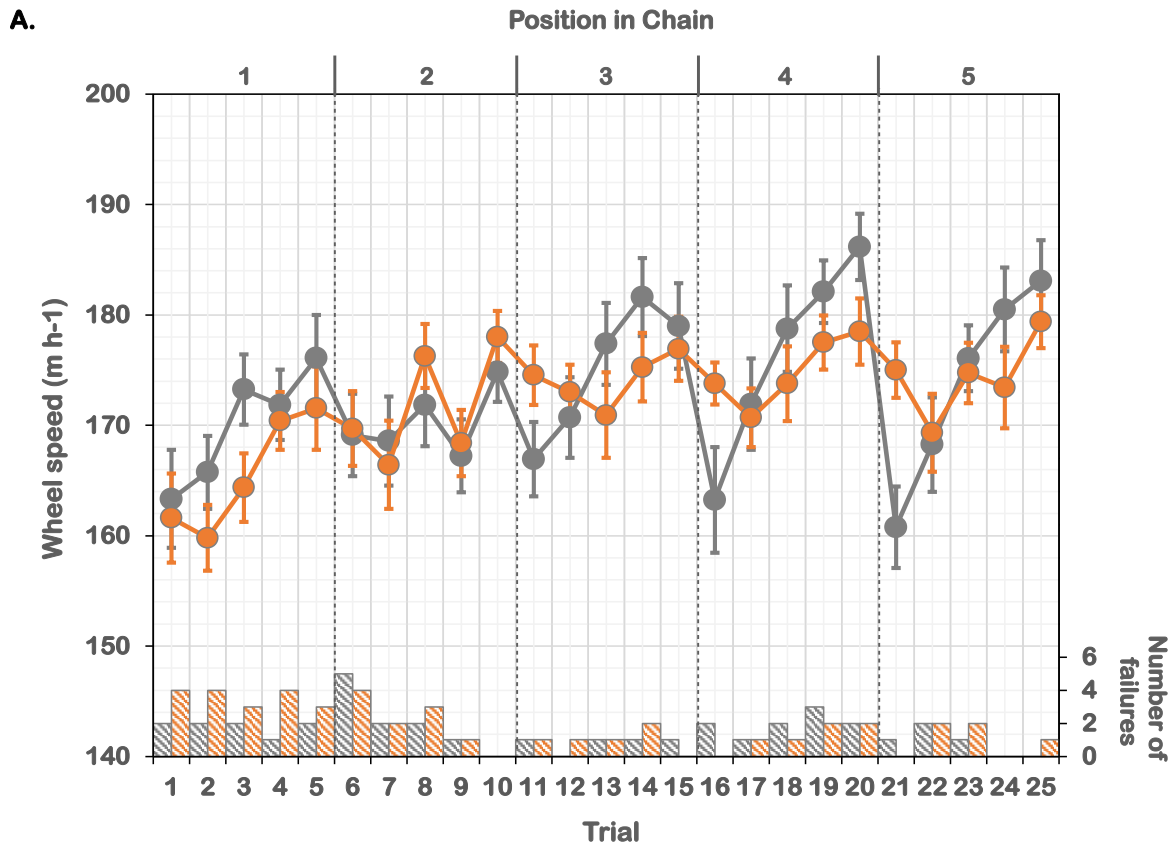


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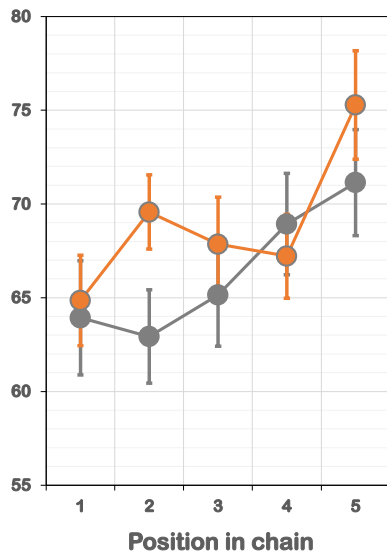
545 **Fig. 1. Experimental task and design.** **A.** The task consisted of minimizing the time it took a wheel to travel  
 546 down an inclined track. The wheel had four radial spokes. On each spoke, a weight could be moved closer to or  
 547 further from the center of the wheel on 12 positions. **B.** The participants performed the task as members of  
 548 chains of five participants. Each of the participants had five trials to improve the wheel system by modifying the  
 549 wheel configuration. The experimenter transmitted to each participant (except those of the first generation) the  
 550 information about the last two trials (grey) of the previous participant. After the five trials, the participants'  
 551 understanding of the wheel system was assessed with an understanding test (12 center-of-mass items and 12  
 552 inertia items). **C.** In the Speed-Only condition, only the wheel speeds of the last two trials (grey) were  
 553 transmitted to the next participant. In the Configurations+Speed+Noise condition, the participants were given

554 two weight configurations and their associated speeds. The configurations came from the previous participant in  
555 the chain but were modified by randomly moving the four weights six positions closer to or farther from the  
556 center of the wheel.

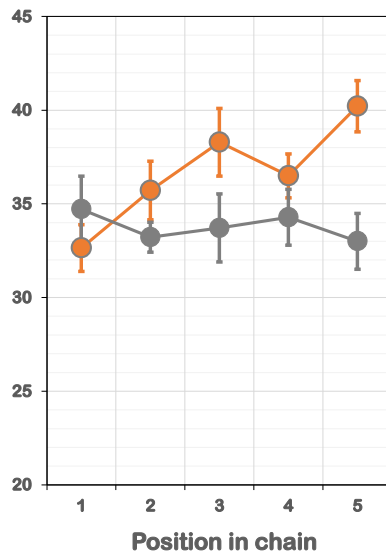
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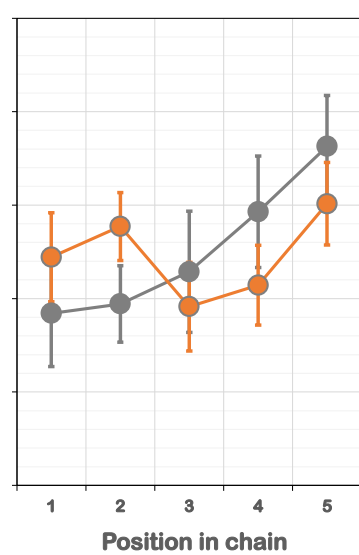
**B.** Understanding (Total)



**C.** Understanding (Center of mass)



**D.** Understanding (Inertia)



● Speed Only ● Configurations+Speed+Noise

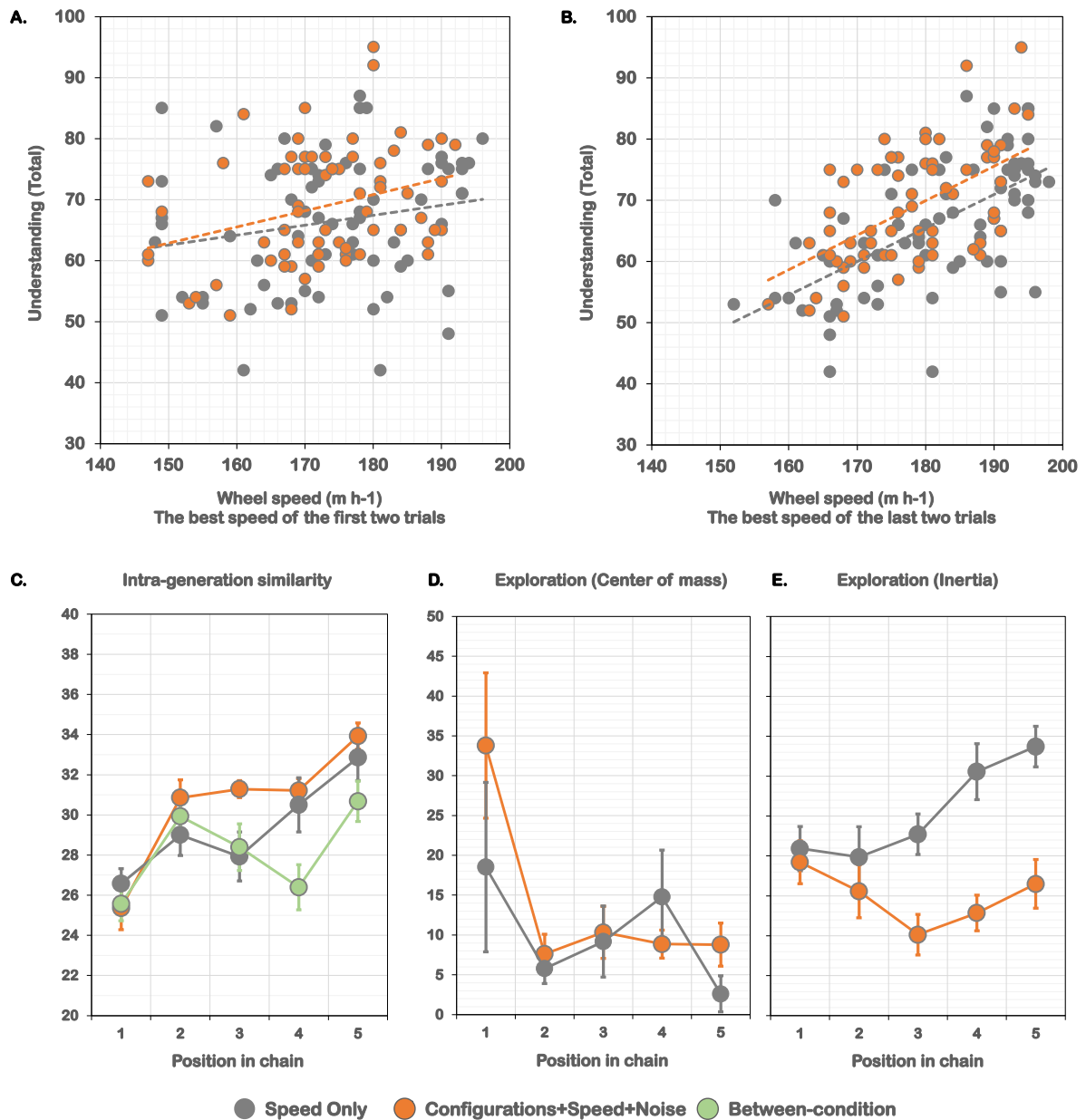
558

559 **Fig. 2. Parallel improvement of the wheel system and of its understanding.** A. Wheel speed over generations  
 560 for non-failure wheels and number of failures in the Speed-Only condition (grey) and in the  
 561 Configurations+Speed+Noise condition (orange). B-D. Understanding scores over generations (B: Total; C:



562 Center-of-mass items only; D: Inertia items only). The performance obtained by a control group is also shown  
563 [see (41); Mean: Yellow; Standard Error: Blue]. Error bars indicate standard errors.

564



565

566 **Fig. 3. Links between the wheel speed and the understanding scores and increase of intra-generation**  
 567 **similarity and exploration scores over generations. A-B.** Links between the wheel speed (A: The best speed  
 568 of the first two trials; B: The best speed of the last two trials) and the understanding scores (Total). **C.** Intra-  
 569 generation similarity scores over generations (Within-condition: Speed-Only condition, Grey;  
 570 Configurations+Speed+Noise condition, Orange; Between-condition: Green). **D-E.** Exploration scores (D:  
 571 Center of mass; E: Inertia) over generations. Error bars indicate standard errors.