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**Roles of Technical Reasoning, Theory of Mind, Creativity, and Fluid Cognition in
Cumulative Technological Culture**

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Abstract

Cumulative technological culture can be defined as the progressive diversification, complexification and enhancement of technological traits through generations. An outstanding issue is to specify the cognitive bases of this phenomenon. Based on the literature, we identified four potential cognitive factors, namely, theory-of-mind, technical-reasoning, creativity, and fluid-cognitive skills. The goal of the present study was to test which of these factors – or a combination thereof – best predicted the cumulative performance in two experimental, micro-society conditions (i.e., Communication and Observation conditions; $n = 100$ each) differing in the nature of the interaction (i.e., verbal, visual) allowed between participants. The task was to build the highest possible tower. Participants were also assessed on the four aforementioned cognitive factors in order to predict cumulative performance (tower height) and attractiveness. Our findings indicate that technical-reasoning skills are the best predictor of cumulative performance (tower height), even if their role may be restricted to the specific technological domain. Theory-of-mind skills may have a facilitator role, particularly in the Communication condition. Creativity can also help in the generation of novel ideas, but is not sufficient to support innovation. Finally, fluid cognition is not involved in cumulative technological culture. Taken together, these findings suggest that domain-specific knowledge (i.e., technical-reasoning skills) remains critical for explaining cumulative technological culture.

Introduction

Culture is a dynamic process. Through the social diffusion of artifacts, behaviors and ideas, individuals attached to a group progressively modify these traits, either intentionally or accidentally, thus leading to cultural evolution. This cultural evolution can be illustrated through the history of hominin stone tool making. From the earliest known stone tools dated to 2.5/3.3 mya (Harmand et al. 2015; Semaw et al. 2007), humans have progressively developed and combined artifacts involving in critical activities, such as foraging, or hunting. This progression has not always been exponential. In the period of time between the beginning of the Oldowan and the appearance of metal cutting tools (approximately 6000 years ago; Whiten 2015), the archaeological record indicates vast periods of time when there was no considerable cultural change. This is only recently that an exponential progression has emerged not only in the technological domain but also in other domains (e.g., chemistry, mathematics, medicine; Lehman 1947). This phenomenon is called Cumulative Technological Culture (CTC), namely the progressive diversification, complexification and enhancement of cultural traits through generations (ratchet effect; Tomasello et al. 1993). Even though different species are suspected to possess the ability to accumulate cultural traits — such as primates (Claidière et al. 2014; Davis et al. 2016), mammals (Thornton and Malapert 2009) and birds (Mueller et al. 2013; Sasaki and Biro 2017) —, only humans produce cultural traits now so complex that they are inaccessible to the competency of isolated individuals (Boyd et al. 2011). So, the critical question is to understand the cognitive bases of this phenomenon.

A first answer to this question has been given by the influential shared intentionality theory (i.e., theory-of-mind skills; Hermann et al. 2007; Tomasello et al. 1993, 2005). By understanding the learner's intentions and mental representations of a task, the teacher is more

likely to give appropriate feedback and, as a result, to help her/him to reproduce the technique targeted to perform the task. In this way, theory-of-mind skills might play an important role in faithful transmission (i.e., imitation), one of the two engines of CTC (see below for the other engine, innovation; Legare and Nielsen 2015). Faithful transmission has been considered as critical to CTC, especially when large populations are concerned (Lewis and Laland 2012), in order to prevent the progressive loss of information through time. Nevertheless, empirical evidence has revealed that, under specific circumstances, fidelity is not necessary for the emergence of a ratchet effect. More specifically, Caldwell and Millen (2009; see also Caldwell et al. 2012) demonstrated that the progressive improvement of a performance was still possible under conditions in which participants did not reproduce the same behaviors as their predecessors. These findings question the so-called need for faithful transmission in CTC and, as a result, the role played by theory-of-mind skills.

The critical role of theory-of-mind skills in CTC has also been recently discussed based on studies using micro-society paradigms, which have found that cumulative performance could be also observed in situations of reverse engineering (i.e., scrutinizing of the end-product), that is, in situations where teachers and learners do not communicate at all (Caldwell and Millen 2009; Caldwell et al. 2017; Zwirner and Thornton 2015). This has led to consider that a key cognitive process might be at work in any context of CTC (e.g., teaching, observation, reverse engineering), namely, the ability to reason about physical object properties, also called technical reasoning (Osiurak et al. 2016; Zwirner and Thornton 2015; see also Osiurak and Heinke 2018; Osiurak and Badets 2016; Osiurak et al. 2010; Reynaud et al. 2016), a concept very close to those of naïve physics reasoning (McCloskey 1983), analogical reasoning (Penn et al. 2008; Povinelli 2000), causal beliefs (Wolpert 2003), causal reasoning (Vaesen 2012) or mechanical

reasoning (Hegarty 2004). Evidence has indicated that technical-reasoning skills might be at work not only when making novel tools, but also when using familiar tools (e.g., a knife; see Goldenberg and Hagmann 1998; Goldenberg and Spatt 2009; Osiurak et al. 2009; see also Johnson-Frey 2003; McCormak et al. 2011). By reasoning technically, a learner can not only extract relevant information from the end-product or predecessor/teacher's demonstration in order to reproduce it (i.e., imitation), but also reject irrelevant information as well as generate new ideas to improve the end-product (i.e., innovation, the second engine of CTC; Legare and Nielsen 2015). A recent micro-society study also indicates that participants' technical-reasoning skills are a better predictor of cumulative performance than participants' theory-of-mind skills in both an observation condition and a communication condition (Osiurak et al. 2016). Nevertheless, technical-reasoning skills might be partly insufficient when the building process of an artifact is opaque, that is, hard to infer from scrutinizing the end-product itself (Wasielewski 2014; see also Caldwell et al. 2017; Morgan et al. 2015; Stout and Hecht 2017). In this case, the teacher's theory-of-mind skills might be useful to transmit appropriately information to the learner (Morgan et al. 2015).

The emphasis has been so far on theory-of-mind and technical-reasoning skills, perhaps because CTC corresponds to the *social* transmission of *technical* information. However, more general cognitive aptitudes can take part in CTC (Kendal et al., 2018) notably if we consider that innovation is one engine of this phenomenon. Creativity being the ability to produce new and original ideas (Guildford 1967), the link between innovation and creativity is straightforward. As stated by Enquist et al. (2008), creativity could be a prerequisite for CTC, both at the origin of and during the evolutionary process, even if too much creativity can be in disfavor of CTC. Even if the role of creativity in CTC has been repeatedly addressed (Carr et al.

2016; Enquist et al. 2008; Fogarty et al. 2015; Legare and Nielsen 2015), no study has ever tested it directly, in an empirical way.

To be innovative, a production needs to be new but also adapted. In this way, another general cognitive aptitude that could take part in CTC is fluid cognition, namely, the ability to maintain temporarily information in order to produce adapted responses to solve novel problems or plan and execute directed behavior (Blair 2006). The link between CTC and fluid cognition, or intelligence more generally, has been only slightly addressed in the field of social learning. A recent study nevertheless addressed the issue of which kind of psychological features support faithful transmission of cultural material (Muthukrishna et al. 2016). In particular, they showed that IQ is linked to the rate of conformist transmission, the extreme values of IQ leading to the highest rates. This result is somehow counterintuitive as we could expect that the highest IQ should lead people to innovate and not to copy faithfully.

To sum up, we have identified four potential cognitive factors of CTC, namely, theory-of-mind, technical-reasoning, creativity, and fluid-cognitive skills. The goal of the present study was to test which of these factors – or a combination thereof – best predicted CTC. We used a transmission chain paradigm (Caldwell and Millen 2009; Osiurak et al. 2016) where participants had to build the highest possible tower. As social transmission can be supported by verbal and/or non-verbal interactions (e.g., visual), we reproduced these two modes of transmission with two micro-society conditions. In the Communication condition, teachers and learners could communicate verbally. In the Observation condition, learners could observe teachers' building behavior without communicating with them. We also added a Control condition to verify that the potential presence of cumulative performance in our two micro-society conditions was higher than in a condition where a same individual has to repeat the task

several times in a row. Participants were also assessed on the four aforementioned cognitive factors in order to predict cumulative performance (tower height) and attractiveness.

Methods

Two hundred and ten undergraduate students in cognitive sciences at the University of Lyon ($M_{Age} = 19 \pm 1.4$, 132 females) took part in the experiment. Two hundred were assigned to the two experimental conditions of the micro-society paradigm (i.e., Communication and Observation; $n = 100$ for each condition) and the remaining ten were assigned to the Control condition. The sample size was estimated from the results of Caldwell and Millen (2009) and Osiurak et al. (2016) who used the same paradigm as in the present work (i.e., conditions with 10 chains of 10 participants each). The study was approved by the Ethics Committee of the Department of Psychology of Lyon, and informed consent was obtained from all participants.

The main task consisted in building the highest possible tower with 15 20-cm-steel wires. Participants performed the task (5 min long) as members of a transmission chain, each of them being progressively replaced one after the other until the last participant completed the task (chain length = 10 participants). In the Communication condition, participants began by building the tower. Then, they could observe the next participant completing the same task and share advices with her/him (no direct demonstration was allowed, only verbal exchange). In the Observation condition, participants could watch their predecessor performing the task without communicating with them. Then, they carried out the task while being observed by another participant, and so forth. In the Control condition, participants were asked to build the highest possible tower and then to repeat the process 10 times in a row. Two measures were collected from the main task. The first was the height of towers in cm. Each tower was positioned vertically and the measure was taken only after 10s. Therefore, the measure was sometimes taken

on towers that had fallen down. The height corresponded to the distance between the table and the highest vertical point of the tower, but not to the total length of the tower. The second measure (attractiveness) was based on specific features of the shape of towers. There were four features: Convergence of feet (Yes *versus* no); Presence of a base (Yes *versus* no); Presence of intermediary columns (Yes *versus* no); Presence of an antenna (Yes *versus* no). The attractiveness score corresponded to the number of similar features between Participant n and Participant $n+1$. Given that there were four features, the maximum attractiveness score was 4. The higher the attractiveness score was the more attractive Participant n was. Note that Participant 10 had no attractiveness score because s/he had no successor.

After the main experiment, participants had to complete an individual testing session during which they were assessed on tasks assessing the four cognitive factors identified, namely, theory-of-mind, technical-reasoning, creativity, and fluid-cognitive skills (for a similar procedure, see Osiurak et al. 2016).

Theory-of-mind skills were measured with two tests. The first is the “Reading-the-Mind-in-the-Eyes” (RME) test (Prevost et al. 2014). It consists in choosing which of four words best describes what the person in the photograph is feeling or thinking (36 items; time limit: 3 min). The second, the comic strip (CS) task (Sarfaty et al. 1997), corresponds to short three-pictures comic strips, showing a character performing a very simple action. The task is to choose which one of three answer cards is the most logical to complete the comic strip sequence (28 items; time limit: 2 min). For each test, we recorded the number of correct responses given within the time limit.

For technical-reasoning skills, they had to complete two sub-tests of the NV7 battery (Bernaud et al. 1994; NV7a: e.g., selecting among four pictures depicting four different nails the

easiest one to hammer; 24 items; time limit: 5 min; NV7b: e.g., selecting among four 3D geometrical shapes the one corresponding to a given 2D pattern; 38 items; time limit: 5 min). For each test, we recorded the number of correct responses given within the time limit. The items used in these tests were very similar to those used in experimental studies on “mechanical reasoning” (e.g., water pouring problems or pulley problems; for more detail, see Hegarty 2004) and, as a result, were a good proxy for assessing the understanding of how the physical world works.

Creativity was measured with the Idea Generation Task (IGT; Finke et al. 1992) and Guilford’s Alternative Uses test (GAU; Guilford 1967). The IGT consists in a set of three abstract pictures for which participants must describe the kind of tool or invention, real or imaginary, they can represent. Instructions are to give as many ideas as possible for each item, with as much details as possible (Time limit: 5 min). The GAU is composed of three objects (a brick, a shoe, and a sheet of newspaper), for which participants are asked to list all the possible ways each of them could individually be used for. These uses could be common (e.g., use newspapers reading the news) or uncommon (e.g., use newspaper as a tablecloth). Again, participants must give as many ideas as possible for each item, with as much details as possible (Time limit: 5 min). For both tests, an individual score was computed based on the sum of four indices (Torrance 1972, 1988):

- Productivity/fluency: the total number of ideas produced by the subject;
- Flexibility: the number of different categories in which these ideas could be put in;
- Elaboration: the number of details given for each idea;

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- Originality: in the GAU, each response is compared to the total amount of answers given by all the participants. Responses that were given by only 5% of their group are qualified as unusual (1 point), all other responses are counted with 0 points. In the IGT, originality is an arbitrary score rated by a judge, varying between 1 (“*not original at all*”) and 5 (“*highly original*”).

Fluid cognition was also measured with two tests: Raven’s progressive matrices (RPM) test (Raven 1960) and the D2000 test (Grégoire 2004). The RPM consists in puzzles with missing pieces. Participants are asked to select the correct piece among several distractors. The test includes 5 sets of twelve puzzles, each set being more difficult than the previous. Participants had to give as many correct answers as possible before reaching the time limit (5 min). The D2000 test follows the same rule as the RPM. Participants were presented with different series of dominoes which numbers followed each other according to an implicit rule. The task is to find that rule by understanding the relation(s) between the dominoes and, then, to apply that rule to find the missing domino at the end of the series (40 items; time limit: 13 min). The answer is generated by participants instead of choosing it among a set of distractors as in the RPM test. For each test, we recorded the number of correct responses given within the time limit.

A pilot study ($n = 245$ undergraduate students) was used to confirm that each pair of tests (RME/CS *vs.* NV7a/NV7b *vs.* IGT/GAU *vs.* RPM/D2000) was associated with the specific cognitive factor expected (Theory of mind *vs.* Technical Reasoning *vs.* Creativity *vs.* Fluid cognition, respectively). We conducted a factorial analysis with varimax rotation that revealed a four-factor solution accounting for 77% of total variance (Factor 1: 15%; Factor 2: 21%; Factor 3: 19%; Factor 4: 22%). Factor 1 mainly loaded on RME (.94) and CS (.47), Factor 2 on NV7a (.80) and NV7b (.66), Factor 3 on IGT (.88) and GAU (.81), and Factor 4 on RPM (.81) and

D2000 (.86). These analyses confirmed that RME/CS, NV7a/NV7b, IGT/GAU, and RPM/D2000 were orthogonal measures of theory-of-mind, technical-reasoning, creativity, and fluid-cognitive skills, respectively. For the present study, we obtained a composite score for each of the four cognitive factors studied here by computing, first, a standard z -score for each test and then by averaging the two scores corresponding to each cognitive factor.

Results

Results of the two micro-society conditions (Observation and Communication) and the Control condition are displayed in **Figure 1**. In each condition, we tested for cumulative performance (tower height) by using the nonparametric Page's test (Caldwell and Millen 2009). There was a significant improvement over generations for the two micro-society conditions (Communication: $p < .02$; Observation: $p < .001$) as well as for the Control condition ($p < .05$). As recommended by Caldwell et al. (2017) and Reindl and Tennie (2018), we confirmed our results from Page's test with a LMM using R (R Core Team 2013) with tower height as dependent variable, generation (i.e., position of the participant in the chain) as fixed effect and chain number as a random effect using the "lmer" function of the R package lme4 (Bates et al. 2013). For each condition, we tested the overall significance of the model by comparing the conditional model to a null model lacking generation but chain number as a random effect with an F -test. This analysis confirmed the results obtained from Page's test with an effect of generation for the three conditions (Communication: $p < .05$; Observation, $p < .001$; Control: $p < .02$). To examine whether cumulative performance was higher in the micro-society conditions than in the Control condition, we computed for each condition a Δ -score defined as the mean performance of the last 3 participants (attempts in the Control condition) minus the mean performance of the first 3 participants (attempts in the Control condition; **Figure 1**). This Δ -score

was submitted to Mann-Whitney comparisons, indicating that the Δ -score was almost significantly higher ($p = .065$) in the Observation condition ($M = 17.07$ cm, 95% $CI = 6.01$ cm–28.12 cm) than in the Communication condition ($M = 7.13$ cm, 95% $CI = -0.28$ cm–14.55 cm) and also almost significantly higher ($p = .093$) than in the Control condition ($M = 6.40$ cm, 95% $CI = -5.41$ cm–18.21). The Communication condition and the Control condition did not differ from each other ($p = .45$).

< INSERT FIGURE 1 ABOUT HERE >

We then focused on the evolution of attractiveness over the generations and between the conditions (**Figure 1**). Results obtained from the Page's test revealed an increase of attractiveness in the Communication condition (Page's L trend test, $p = .033$) and in the Observation condition ($p < .01$) but not in the Control condition ($p > .05$). These results were partially confirmed with the LMM analyses described above because an increase was found for the three conditions (Communication: $p < .03$; Observation, $p < .001$; Control: $p < .02$). We also computed for each condition a Δ -score defined as the mean attractiveness of the last 3 participants minus the mean performance of the first 3 participants (**Figure 1**). This Δ -score was submitted to Mann-Whitney comparisons. No significant difference was found between the three conditions (all $p > .18$; Communication: $M = 0.50$, 95% $CI = -0.01$ –1.01; Observation: $M = 0.77$, 95% $CI = 0.38$ –1.16; Control: $M = 0.50$, 95% $CI = -0.01$ –1.01).

To examine the potential link between our two measures of interest (i.e., tower height and attractiveness) and the four cognitive factors identified above, we first conducted correlational analyses (**Table 1**). Concerning tower height, results indicated that technical-reasoning skills were positively correlated to tower height in both conditions. In the Observation condition, a statistical trend suggested that creativity skills were also negatively correlated to

tower height. Concerning attractiveness, a positive link was found with theory-of-mind skills in the Communication condition, and with creativity skills in the observation condition. To go further, the influence of the four predictors on tower height for each micro-society condition (Communication and Observation) was tested using a LMM, in which the four cognitive factors were included as fixed factors, while chain number was included as random factors using R (see above). For the Communication condition, there were five top candidate models for the Communication condition and two for the Observation condition (**Table 2**). We conducted conditional-model averages based on Akaike Information Criteria value corrected for small sample size (AIC_c ; **Table 3**). The only statistically significant predictors of tower height are technical reasoning in the Communication condition and creativity (in a negative way) in the Observation condition. These two predictors were significant at the 95% confidence level. The same analysis was performed for attractiveness. As shown in **Table 4**, there were two top candidates for both conditions. However, conditional-model averages based on AIC_c did not reveal any significant predictor for both conditions (**Table 5**). Note that theory-of-mind and creativity skills were nevertheless the two cognitive factors that predicted the most attractiveness in the Communication condition and in the Observation condition, respectively. To sum up, LMM analyses globally confirmed the results obtained from correlational analyses.

< INSERT TABLES 1-5 ABOUT HERE >

Discussion

The first key finding is that technical-reasoning skills are the best predictor of cumulative performance (tower height) in both micro-society conditions, confirming previous results obtained in the same conditions (i.e., Observation and Communication), but with a different task (i.e., paper-plane building; Osiurak et al. 2016). This finding is somewhat

counterintuitive based with regard to the literature, where emphasis is more frequently put on the social-cognitive aspects of CTC. However, it is consistent with previous work indicating that CTC can be found even in situations of indirect transmission such as reverse engineering (Caldwell and Millen, 2009; Caldwell et al. 2017; Zwirner and Thornton 2015). Interestingly, the technical-reasoning hypothesis provides a parsimonious way to account for the two engines of CTC (Legare and Nielsen 2015), by explaining not only how people extract relevant technical information from their predecessors (i.e., imitation) but also reject irrelevant information to improve the end-product (i.e., innovation). Nevertheless, the role played by technical reasoning may be limited to CTC and should not to be generalized to other forms of cumulative culture (e.g., music), where other domain-specific skills (e.g., mathematics) may play the role played here by technical-reasoning skills.

The second key finding is that theory-of-mind skills do not predict cumulative performance (tower height) in none of the two micro-society conditions, thereby corroborating previous results with the same experimental conditions (Osiurak et al. 2016). This rules out a strong version of the shared intentionality theory of CTC that would suggest that theory-of-mind skills are critical to CTC. A weaker version of this theory may be that theory-of-mind skills are not the key cognitive factor of CTC – contrary to technical-reasoning skills – but can nevertheless participate under some circumstances as a facilitator of social transmission. This facilitator role in cumulative culture could occur irrespective of the domain concerned, again contrary to technical-reasoning skills that may be restricted to the technological domain. For instance, theory-of-mind skills may help to transmit information more faithfully but only when learners and teachers can communicate (Claidière and Sperber 2007), as suggested by the relatively weak link we found here between theory-of-mind skills and attractiveness in the

Communication condition. In broad terms, our findings may help to refine the distinct roles of theory-of-mind and technical-reasoning skills in CTC.

The third key finding is that creative people are attractive even if their production can be ineffective, suggesting a somewhat counterproductive role of creativity, particularly in the Observation condition. Interestingly, this suggests that people may be attracted by original productions such as those generated by the most creative people. In a way, creativity can play an interesting role by providing ideas that are original without being necessarily effective, as evidenced by the negative link found between creativity and tower height in the Observation condition. However, if less creative participants had followed the productions made more creative participants, we should not have observed a cumulative effect. So, a potential interpretation is that creativity plays a role of generator of new, original ideas (the divergent component of creativity; Guilford, 1967) that can then be evaluated as adapted/feasible or not by another cognitive process, namely, technical-reasoning skills (the convergent component of creativity; Guilford, 1967). In other words, creativity skills alone are not sufficient to boost CTC and notably the innovative aspect of CTC (see Enquist et al. 2008).

The fourth key finding is the absence of any involvement of fluid cognition in CTC. Fluid cognition is supposed to provide people with the ability to generate adapted responses to solve novel problems (Blair 2006). In this respect, fluid-cognitive skills should be fundamental for CTC, and particularly for the innovative aspect. Our results clearly rule out this possibility as well as the possibility that fluid cognition might correspond to the convergent component of innovation, allowing people to test the feasibility of ideas generated through the divergent component. As suggested above, this convergent component might be specific to the domain concerned by cumulative culture, namely, technical-reasoning skills for CTC. This also stresses

that causal reasoning can take several forms, depending on the domain identified, leading us to specify what is meant by causal reasoning (Zwirner and Thornton 2015). Technical reasoning is a form of causal reasoning, allowing us to foresee the potential outcomes of mechanical actions on the environment (Osiurak and Badets 2016, 2017). This is also true for fluid cognition. However, perhaps fluid cognition is more domain-specific than we think. It might be specific to the domain of abstract or logical relationships that do not need to be true in the physical world. So, an interesting possibility is that fluid cognition might be critical in some forms of cumulative culture where people have to do abstract reasoning (e.g., syllogistic reasoning; see Trouche et al. 2016).

The goal of the present study was to identify the cognitive factors of CTC. Our findings indicate that technical-reasoning skills are the best predictor of CTC, even if its role may be restricted to the specific technological domain. Theory-of-mind skills may have a facilitator role, particularly when people can communicate. Creativity can also help in the generation of novel ideas, but is not sufficient to support innovation. Finally, fluid cognition is not involved in CTC. Taken together, these findings suggest that domain-specific knowledge might remain critical for explaining CTC and more generally any forms of cumulative culture. This conclusion needs to be tempered because of the paradigm chosen here, which had several limitations. For instance, the teachers were imposed by the experimenter and not chosen by the learners, thereby diverging from everyday life where people decide which model to copy by developing social learning strategies (Mesoudi 2008). So, in such a context, theory-of-mind skills might be involved in order to determine who is the best model to copy. Likewise, our task was relatively transparent in that the end-product (i.e., the tower) provided enough information about how it was built when looking at it. However, as mentioned in Introduction, theory-of-

mind skills might be more particularly involved when the task is opaque in order to provide the background knowledge that governs the building process (Morgan et al. 2015; see also Csibra and Gegerly 2006). Finally, remind that the exponential progression characterizing CTC remains relatively recent and certainly more recent than the emergence in the hominin lineage of the cognitive factors assessed here. Therefore, even if the present findings offer new insights into our understanding of the cognitive origins of CTC, further research is needed to explore how these different factors could have contributed to the development of CTC.

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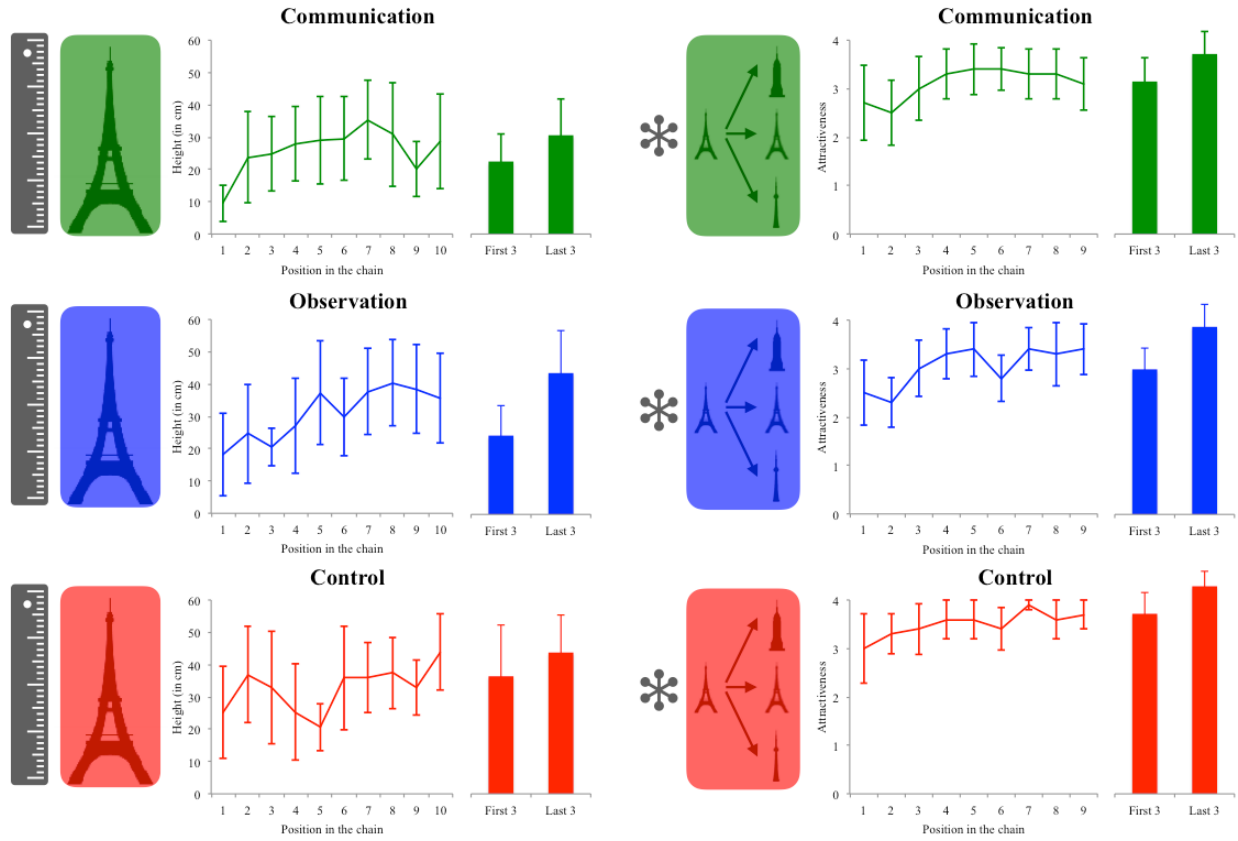


Figure 1. Results (tower height and attractiveness) of the two micro-society conditions (Communication and Observation) and the Control condition. Error bars represent 95% confidence intervals.

Cognitive Bases of Cumulative Technological Culture

Table 1.

Correlational analyses between our measures of interest (tower height and attractiveness) and the four cognitive factors studied here

Communication				
	Theory of mind	Technical reasoning	Creativity	Fluid cognition
Tower height	.11	.22*	.01	.12
Attractiveness	.22*	.11	.11	.04
Observation				
	Theory of mind	Technical reasoning	Creativity	Fluid cognition
Tower height	-.08	.14 ^x	-.13 ^x	.06
Attractiveness	.08	.15 ^x	.20*	.09

Correlations are Pearson correlation coefficients ($n = 100$ for each condition for tower height; $n = 90$ for each condition for attractiveness). ^x $p < .10$; * $p < .05$

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Table 2

Best models of cumulative performance (tower height) in the two micro-society conditions (LMM analysis)

Communication condition					Observation condition				
Models	k	AICc	Δ_i	ω_i	Models	k	AICc	Δ_i	ω_i
<i>Tech</i>	4	873.80	0.00	0.19	<i>Crea</i>	4	885.53	0.00	0.31
<i>Tech+Fluid</i>	5	874.21	0.41	0.15	<i>Tech+Crea</i>	5	886.41	0.87	0.20
<i>Fluid</i>	4	874.54	0.74	0.13	Crea+ToM	5	887.72	2.18	0.10
<i>Tech+ToM</i>	5	874.75	0.95	0.12	Crea+Fluid	5	887.75	2.21	0.10
<i>Fluid+ToM</i>	5	875.76	1.96	0.07	Tech+Crea+ToM	6	888.33	2.80	0.08
Tech+Fluid+ToM	6	875.90	2.10	0.06	Tech+Crea+Fluid	6	888.35	2.82	0.08
Tech+Crea	5	876.02	2.22	0.06	Crea+Fluid+ToM	6	889.96	4.42	0.03
Tech+Crea+Fluid	6	876.43	2.63	0.05	Tech+Crea+Fluid+ToM	7	890.50	4.96	0.03
Crea+Fluid	5	876.72	2.92	0.04	ToM	4	890.94	5.41	0.02
Tech+Crea+ToM	6	876.94	3.14	0.04	Tech+ToM	5	892.01	6.48	0.01
ToM	4	877.32	3.52	0.03	Tech	4	892.03	6.50	0.01
Crea+Fluid+ToM	6	877.87	4.07	0.02	Fluid	4	892.27	6.73	0.01
Tech+Crea+Fluid+ToM	7	878.10	4.30	0.02	Fluid+ToM	5	893.08	7.54	0.01
Crea+ToM	5	879.47	5.67	0.01	Tech+Fluid	5	893.85	8.31	0.00
Crea	4	881.41	7.61	0.00	Tech+Fluid+ToM	6	894.26	8.72	0.00

ToM, theory-of-mind skills; Tech, technical-reasoning skills; Crea, creativity skills; Fluid, fluid-cognitive skills; k , number of parameters in the model; AICc, Akaike's Information Criterion corrected, $\Delta_i = \text{AIC}_{c(i)} - \text{AIC}_{c(\min)}$; ω_i , Akaike weights explaining total variance. Models with $\Delta_i < 2$ are in italics.

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Table 3

Predictors from the conditional-averaged model of cumulative performance (tower height)

Communication condition			Observation condition		
Predictors	Estimate±SE	Importance weight	Predictors	Estimate±SE	Importance weight
Tech	5.07±2.57*	0.69	Crea	-5.97±2.24*	0.93
Fluid	4.85±2.98	0.55	Tech	2.96±2.51	0.41
ToM	3.02±2.82	0.38	ToM	-1.32±2.90	0.28
Crea	-0.47±2.35	0.25	Fluid	-0.45±2.53	0.26

ToM, theory-of-mind skills; Tech, technical-reasoning skills; Crea, creativity skills; Fluid, fluid-cognitive skills; Estimate, Weighted parameter estimate; SE, Standard error; *, Variables that are significant at the 95% confidence level (the interval does not contain the null value).

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Table 4

Best models of evolution of attractiveness in the two micro-society conditions (LMM analysis)

Communication condition					Observation condition				
Models	k	AICc	Δ_i	ω_i	Models	k	AICc	Δ_i	ω_i
<i>ToM</i>	4	244.18	0.00	0.22	<i>Crea</i>	4	244.25	0.00	0.25
<i>Crea</i>	4	245.22	1.04	0.13	<i>Tech</i>	4	246.10	1.84	0.10
<i>Crea+ToM</i>	5	245.59	1.41	0.11	Tech+Crea	5	246.34	2.09	0.09
<i>Fluid+ToM</i>	5	246.01	1.82	0.09	ToM	4	246.35	2.10	0.09
Tech+ToM	5	246.42	2.24	0.07	Crea+Fluid	5	246.36	2.11	0.09
Tech	4	246.74	2.55	0.06	Crea+ToM	5	246.45	2.20	0.08
Fluid	4	246.97	2.79	0.06	Fluid	4	246.61	2.36	0.08
Tech+Crea	5	247.33	3.15	0.05	Tech+Fluid	5	248.06	3.81	0.04
Crea+Fluid+ToM	6	247.36	3.18	0.05	Tech+Crea+Fluid	6	248.26	4.01	0.03
Crea+Fluid	5	247.46	3.28	0.04	Tech+ToM	5	248.27	4.02	0.03
Tech+Crea+ToM	6	247.88	3.69	0.04	Fluid+ToM	5	248.45	4.20	0.03
Tech+Fluid+ToM	6	248.20	4.01	0.03	Tech+Crea+ToM	6	248.52	4.27	0.03
Tech+Fluid	5	248.98	4.79	0.02	Crea+Fluid+ToM	6	248.65	4.40	0.03
Tech+Crea+Fluid	6	249.56	5.38	0.02	Tech+Fluid+ToM	6	250.16	5.91	0.01
Tech+Crea+Fluid+ToM	7	249.62	5.44	0.01	Tech+Crea+Fluid+ToM	7	250.58	6.33	0.01

ToM, theory-of-mind skills; Tech, technical-reasoning skills; Crea, creativity skills; Fluid, fluid-cognitive skills; k , number of parameters in the model; AICc, Akaike's Information Criterion corrected, $\Delta_i = \text{AIC}_{c(i)} - \text{AIC}_{c(\min)}$; ω_i , Akaike weights explaining total variance. Models with $\Delta_i < 2$ are in italics.

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Table 5

Predictors from the conditional-averaged model of evolution of attractiveness

Communication condition			Observation condition		
Predictors	Estimate±SE	Importance weight	Predictors	Estimate±SE	Importance weight
ToM	0.22±0.13	0.62	Crea	0.17±0.11	0.62
Crea	0.14±0.13	0.44	Tech	0.07±0.12	0.35
Fluid	-0.05±0.15	0.32	ToM	0.02±0.14	0.32
Tech	0.03±0.13	0.30	Fluid	-0.04±0.12	0.32

ToM, theory-of-mind skills; Tech, technical-reasoning skills; Crea, creativity skills; Fluid, fluid-cognitive skills; Estimate, Weighted parameter estimate; SE, Standard error.