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The Elephant in the China Shop: When Technical Reasoning Meets Cumulative Technological Culture

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Running Head: Cumulative Technological Culture and Technical Reasoning

Abstract

The commentaries have both revealed the implications of and challenged our approach. In this response, we reply to these concerns, discuss why the technical-reasoning hypothesis does not minimize the role of social-learning mechanisms – nor assume that technical-reasoning skills make individuals omniscient technically – and make suggestions for overcoming the classical opposition between the cultural *versus* cognitive niche hypothesis of cumulative technological culture.

R1. Introduction

Cumulative technological culture (CTC) is a fascinating phenomenon, considered in 2005 by the journal *Science* as one of the 125 big scientific questions. Research on this topic has been dominated by disciplines such as anthropology, evolutionary biology, mathematics, or archaeology. Some areas of psychology also contribute to the debate (e.g., developmental, comparative). However, this rarely applies to the areas of psychology involved in the cognitive sciences, such as cognitive psychology, neuropsychology or cognitive neuroscience (Heyes 2018). This is surprising if we acknowledge that CTC cannot be fully understood without a detailed examination of its neurocognitive origins. In the target article, we offered a unified cognitive approach to this phenomenon in order to overcome this shortcoming.

Before we begin our response by reminding the reader of the key aspects of our approach, we would like to warmly thank the authors of all 26 commentaries for their thoughtful critiques and the extensions they suggest to the target article. Due to the great number of commentaries, we are unfortunately not able to discuss all of the concerns raised but hope we have done justice to the most important points.

R2. What the elephant says

The key hypothesis of our approach is that CTC originates in non-social cognitive skills, namely technical-reasoning skills which enable humans to acquire new techniques and improve existing ones. This hypothesis leads us to decouple CTC from social-learning mechanisms without, however, wishing to minimize the impact of the latter (**Gruber**). Technical reasoning is a cognitive structure which makes it possible to acquire and elaborate technical content (i.e., mechanical knowledge). It is unaware of the source that provides this content. As rightly emphasized by **Gabora and Smith**, the distinction commonly made between asocial learning and social learning does not exist for technical reasoning. To paraphrase them, we can acquire the technique of peeling by watching a conspecific peel a banana (social learning), by watching a monkey peel a banana (asocial learning) or by watching the petals of a tulip unfold (asocial learning). In all these situations, the same technical reasoning is at work. What differs, however, is the opportunity offered by the environment. In other words, humans can acquire technical content more quickly through social learning – and particularly through complex forms of social

learning such as teaching – than through asocial learning. Nevertheless, the opportunity to acquire technical content (through asocial or social learning) is *orthogonal* to the ability to acquire and improve it (through technical reasoning). As rightly pointed out by **Claidière**, our approach is far more consistent with a social than an ecological view of CTC.

This approach can be misinterpreted as placing exaggerated emphasis on the technical dimension of the phenomenon (e.g., **Houkes & Vaesen**; **Miu, Boyd, Richerson, & Morgan [Miu et al.]**; **Thornton, Happé, & Caldwell [Thornton et al.]**). For instance, it might be considered to lead, by extrapolation, to the idea that “a single human, of infinite lifespan, with infinite time, would be able to produce the entirety of the current human repertoire” (**Miu et al.**). We understand how such a misinterpretation can be arrived at and we think that the main reason is that we did not specify what we meant by “the opportunity offered by the environment”. We would like to correct this omission. Let us consider a solitary species equipped with technical-reasoning skills (Asocial opportunity+; Social opportunity-). This species can acquire technical content through asocial learning (i.e., innovation-by-invention; **Rawlings & Legare**). However, the lack of opportunity to watch other conspecifics should prevent this species from showing signs of CTC, with each individual being systematically condemned to reinvent the wheel. Therefore, some social conditions such as gregariousness and social tolerance are prerequisites for the social transmission of technical skills (van Schaik et al. 1999)¹. Let us now consider a species with such social conditions (Asocial opportunity+; Social opportunity+). Even with less complex forms of social learning (i.e., no teaching), the ability to reason technically about the opportunities offered by the asocial and social environment can lead this species to progressively show signs of CTC, thereby generating a greater number of innovations and, notably, innovations-by-modification (**Rawlings & Legare**). However, the scope of this phenomenon may be limited due to the complexification of technology over time (see sect. 3.3 and 3.4). Thus, more complex forms of social learning based on specific social cognitive skills (i.e., theory of mind; but also language, an aspect overlooked in the target article; see sect. 5; **Claidière**; **Thornton et al.**) can become necessary in order to help boost CTC (Asocial opportunity+; Social opportunity++...+). Having clarified these various issues, we can now address the major concerns raised by the commentators.

R3. Is the elephant novel?

Whiten judged that our approach was “essentially correct in arguing that pervasive claims that special forms of human social learning constitute the primary explanation for our distinctive cumulative technological cultures have neglected an ‘elephant in the room’: Non-social cognition” (pp. XX). As stated, the strength of our approach lies in the epistemological shift we proposed, stressing that CTC is not only a social but also a technical phenomenon. This shift has been influenced by our own scientific background, namely cognitive science, which provides novel insights into the neurocognitive origins of CTC. As discussed in sect. 2.1 (see also Figure 2; Osiurak et al. in press), neuropsychological findings have demonstrated that technical reasoning supports both the use of familiar tools (e.g., using a hammer with a nail) and the use and making of novel tools to solve mechanical problems. Technical reasoning mainly involves the area PF within the left inferior parietal lobe. Interestingly, this brain area is also preferentially activated when people observe tool-use actions performed by others. In other words, this suggests that the same neurocognitive process (i.e., technical reasoning/left area PF) is involved when humans carry out mechanical actions as well as when they watch others doing so (Reynaud et al. 2019). These findings are not anecdotal in a field where it is common to assume that “imitation/social learning” and “innovation/asocial learning” are two orthogonal dimensions of CTC (e.g., **Miu et al.**), and which therefore risks giving rise to only a very restricted account of cognition (**Gärdenfors, Högberg, & Lombard [Gärdenfors et al.]**). Instead, in line with **Gabora and Smith’s** commentary (see sect. R2), these neuroscientific findings indicate that the same cognitive process is at work whatever the nature of the learning (i.e., asocial and social). In this respect, contrary to what **Miu et al.** claim, the cognitive approach we propose offers a fresh look at CTC, as pointed out by **Whiten** and other commentators (**Benge & Scullin; Gärdenfors et al.; Gruber; Haber & Corriveau; Korth; Motes-Rodrigo, Reindl, & Bandini [Motes-Rodrigo et al.]; O’Brien & Bentley; Rawlings & Legare; Rutz & Hunt; Thornton et al.; Tracy**).

Another point that leads us to think that our approach is novel concerns the clarifications provided by some proponents of the cultural niche hypothesis about the role of technical reasoning, an aspect ignored so far (see immediately above). More specifically, **Derex and Boyd** state that “Boyd et al. (2011) and Derex et al. (2019) never claimed that reasoning plays no role

in CC. Rather they argued that the improvement of culturally evolving technology is not *necessarily* tied to individuals' level of understanding" (pp. XX). This statement corresponds to a considerable revision of the initial cultural niche hypothesis and we look forward to reading a future theoretical development of this hypothesis explaining what the precise role of technical reasoning in CTC is and how the cultural niche hypothesis now differs from the cognitive niche hypothesis. We also appreciate the clarification that the authors provided concerning the link between individuals' level of understanding and cumulative improvement. We have to note that this differs from the conclusions drawn by Derex et al. (2019): "These results indicate that complex technologies need not result from enhanced causal reasoning but, instead, can emerge from the accumulation of improvements made across generations" (pp. 446). **Miu et al.** argue that we cited only a single (self-authored) study to support our link between technical reasoning and CTC. Actually, we cited four of our studies (De Oliveira et al., 2019; Osiurak et al., 2016; 2020; in revision). We acknowledge that this remains insufficient. Nonetheless, we have already collected the data from more than 1200 participants who took part in micro-society experiments (some of these data are still unpublished). In all these studies, the conclusion is always the same: Cumulative performance is tied to individuals' level of technical reasoning. In broad terms, these findings invalidate the above prediction made by **Derex & Boyd**. Having said this, we agree with **Derex & Boyd** that "*a more fertile approach* may be to study how both types of abilities reinforce each other" (pp. XX). Indeed, our target article was an attempt in this direction in that our aim was to develop a theoretical framework detailing how technical reasoning can work in concert with social-learning mechanisms in order to favor the emergence of CTC. **Miu et al.** hold that our approach is not sufficient because it does not explain "how individual-level decisions scale up to population-level dynamics" (pp. XX). We agree and we also acknowledge that proponents of the cultural niche hypothesis have developed fruitful computational models of CTC at a macroscopic level. One of our current objectives is to follow this direction by conducting modeling work based on the technical-reasoning hypothesis of CTC. However, to initiate this fertile approach, proponents of the cultural niche hypothesis have also to integrate the key neuroscientific findings reported above as well as the link we identified between each individual's level of technical reasoning and cumulative performance in micro-society experiments.

R4. Is the elephant solitary?

As discussed in sect. R2, the focus placed in the target article on the technical dimension seems to have been misinterpreted or overinterpreted by several commentators. As **O'Brien and Bentley** highlight: “We would argue that this revised assumption in no way allows us to ignore the social dimension and redirect our focus to the nonsocial, strictly technical dimension” (pp. XX). We fully agree with them. As explained, technical reasoning is the cognitive structure allowing individuals to acquire and improve technical content. However, the opportunity to acquire it increases as social-learning mechanisms become more effective (e.g., teaching). Thus, we did not hypothesize that solitary individuals equipped with technical reasoning would exhibit CTC. We also thank **Derex and Boyd** for stressing that “individuals constantly face intense trade-offs and so must allocate their time and energy strategically” (pp. XX). We did not address this point explicitly in the target article, although we agree that social-learning mechanisms (particularly teaching) provide suitable conditions for such strategies² (e.g., deciding to acquire a new technical content through social learning when the cost of asocial learning is high). In broad terms, as pointed out by **Gruber**, our purpose was not to minimize the impact of social learning in CTC, but to shift the focus to the technical dimension by assuming that this phenomenon could not emerge without technical reasoning. More specifically, an aspect of our approach that seems to have been mis/overinterpreted by several commentators is the role of teaching/social demonstration in CTC (e.g., **Derex & Boyd; Gärdenfors et al.; Houkes & Vaesen; Miu et al.; Moll, Nichols, & Pueschel [Moll et al.]; Rawlings & Legare; Thornton et al.**). These commentaries mention several studies in which young children fail to solve tasks by themselves (e.g., using water as a tool, or making a hook), but succeed after social demonstration (Beck et al. 2011; Moll 2018; Nielsen 2013). For some of the aforementioned commentators, this demonstrates that teaching/social demonstration is enough for subjects to acquire technical content, without any need to add technical reasoning to the equation. Here we explain why our approach better fits these findings.

Let us begin with the exclusive hypothesis that teaching/social demonstration is enough to permit the acquisition of technical content. This hypothesis predicts that when a child or an adult is unable to acquire a technique by herself or himself, she or he should succeed after teaching/social demonstration. The study of Cutting et al. (2011) provides data that is useful for

testing this prediction. They reported that 8% and 30% of the 4-5-year-olds and 6-7-year-olds, respectively, were able to make a hook by themselves to reach a target, whereas the values were 79% and 67% after a social demonstration (Experiment 1). The authors also proposed another task consisting in unbending a pipe cleaner to reach a target. In this task, 33% and 56% of the 4-5-year-olds and 6-7-year-olds, respectively, successfully solved this task, whereas 58% and 41% did so after a social demonstration (Experiment 1). These findings indicate that the effect of teaching/social demonstration is far from systematic since a significant number of children did not benefit from social demonstration. In broad terms, these findings invalidate the prediction derived from the exclusive hypothesis of teaching/social demonstration.

It is noteworthy that the discussion initiated in these commentaries is based on the incorrect assumption that technical reasoning alone (i.e., without social learning) can allow individuals to acquire spontaneously any technical content. This mis/overinterpretation corresponds to an omniscient view of technical reasoning (see sect. 2.3). However, we did not hypothesize that technical reasoning is a “magic bullet” (**Miu et al.; Thornton et al.**) making it possible to *spontaneously* and *quickly* understand our physical world or acquire and improve techniques. As detailed in sect. 2.3, individuals acquire techniques (i.e., mechanical knowledge) progressively over time and the opportunities offered by the environment (mostly social) differ between individuals, so that the degree of technical expertise is subject to considerable interindividual variation. The corollary is that not every individual can learn any given technical content at any given time. This idea is perfectly in line with the concept of zone of proximal development (Vygotsky 1978; see sect. 3.5; see also **Haber & Corriveau**). In this frame, the aforementioned developmental studies suggest that teaching/social demonstration can be, under some circumstances, a very effective way for children – although this is also true for adults – to go *just* beyond their zone of proximal development. However, if what is transmitted socially goes *far* beyond this area, the acquisition of a new technical content becomes impossible. In this respect, this explains why some children can benefit from social demonstration while others do not, namely because this acquisition depends on their current level of technical-reasoning skills and, as a result, zone of proximal development.

In other words, the amount of technical information that can be transmitted during a social interaction depends very greatly on the learner’s technical-reasoning skills, as demonstrated in

several of our micro-society experiments (e.g., Osiurak et al. 2016). This interpretation is perfectly consistent with **Haber and Corriveau**, who argue “for a more integrated approach to cumulative technical culture, grounded in sociocultural theory (e.g., Vygotsky, 1978). Such an approach should highlight the important cognitive skills children bring to bear to acquire technical information, yet also recognize that most learning situations occur in interactions with others” (pp. XX). Some of the mis/overinterpretations discussed here might have been avoided if we had written this statement as eloquently as **Haber and Corriveau** have done. In the light of this discussion, we must fine-tune our suggestions concerning the idea that children might not have the technical expertise necessary for them to exhibit CTC (sect. 3.4). We thank **Burdett and Ronfard** for highlighting this concern. Studying social transmission in children can, of course, be a good methodological choice for exploring CTC. Simply, in light of the present discussion, we meant that there can be no doubt that much more care is needed when designing experimental tasks in which the technical solutions fall within the participants' zone of proximal development. This might optimize the chances of observing cumulative performance.

R5. Is the elephant omniscient?

In the target article, we formulated two assumptions that may appear paradoxical, but are not. The first is that technical reasoning enables humans to acquire and generate a great amount of technical content. The second is that individuals acquire techniques (i.e., mechanical knowledge) progressively over time depending on the opportunities offered by the environment, leading to considerable interindividual variations. More specifically, we meant that technical reasoning offers the technical potential to acquire any technique. Nevertheless, these techniques cannot be learned independently of a certain logic of acquisition (i.e., the zone of proximal development discussed above), as nicely illustrated by the work of Baillargeon and colleagues (see sect. 2.3). Thus, humans are not omniscient in terms of techniques and their acquisition is costly in terms of time. In addition, given that humans have developed a vast amount of techniques in distinct technical domains, it is, of course, impossible for a human to acquire all of them during her or his lifetime (i.e., the core principle of CTC). The corollary is that, one day, the techniques of a single domain might be too complex to be acquired and improved in a single lifetime (Mesoudi 2011). Regardless, assuming that each human possesses the technical potential to acquire a great – perhaps infinite – amount of technical content is not inconsistent with the idea that our

lifetimes, along with the very complex form taken by CTC, do not allow humans to master every technique of every domain. The corollary is the growing specialization of the domains of expertise of individuals³.

Following on in this vein, it is conceivable that technical expertise in some domains can be lost due to epidemics that primarily affect the experts involved in these domains. The problem is that the surviving individuals might have developed very little expertise in these domains – perhaps because of their idiosyncratic historical trajectories, which have led them to become experts in other (not necessarily technical) domains. The consequence is that these surviving individuals may be unable to re-develop the lost techniques because their acquisition/discovery falls far beyond the survivors' zone of proximal development in the corresponding domain. The technical potential of these survivors can nevertheless enable them to re-master the lost techniques if experts from the technical domain in question visit and help them to reincorporate these techniques. This example corresponds to the Polar Inuit example provided by **Miu et al.** as a counterargument to our approach. However, as explained here, the technical-reasoning hypothesis of CTC offers an interesting alternative for explaining such phenomena, and one which anchored in a more cognitive and developmental framework.

R6. What the elephant brain tells us about CTC

As stated in sect. R3, one of the strengths of our approach is to include a consideration of the literature on cognitive science in our attempt to understand the origins of CTC. This integrative approach also appears to be fruitful in order to address some concerns raised in several commentaries. Let us start with the question of why we did not use the more generic term “causal cognition/understanding” instead of technical reasoning (**Gabora & Smith; Gärdenfors et al.; Weinstein & Baldwin**). This distinction was initially made on the grounds that technical reasoning is thought to be not only causal but also analogical (sect. 2.1). As stressed, even if some nonhuman animals – including tool-using species – may exhibit signs of causal understanding, evidence is still needed concerning the analogical component (for a similar view, see **Rutz & Hunt; Taylor & Jelbert**). In other words, the terms causal cognition/understanding and technical reasoning cannot be used interchangeably. **Gabora and Smith** and **Gärdenfors et al.** also argue that causal cognition refers to a domain-general ability allowing humans to reason

not only about the physical world but also about the social world. In other words, the emergence of this ability could have led to the joint development of human technical-reasoning and theory-of-mind skills. We agree that theory-of-mind skills are fundamental for inferring how our conspecifics may behave based on our knowledge of their guessed hidden mental states. This is a form of causal reasoning: “I think that Emily has put on makeup *because* she wants to be beautiful for the prom”. Nevertheless, the fact that technical reasoning and theory of mind are two forms of causal reasoning does not mean that they are supported by the same neurocognitive processes. The former is based on knowledge about the mechanical actions that can be performed in the physical world. The latter is based on knowledge about the hidden mental states that humans can possess. This distinction is well illustrated by **Crespi**, who discussed the difference between mechanistic cognition and mentalistic cognition on the basis of the literature on the autism spectrum. A large body of evidence also comes from the neuroscientific literature, which has repeatedly confirmed that technical-reasoning and theory-of-mind skills involve distinct neural networks: The area PF within the left inferior parietal lobe (see sect. 2.1) and the dorsomedial prefrontal cortex, temporoparietal junction, and anterior temporal cortex, respectively (e.g., see Van Overwalle & Baetens 2009; see also Spunt & Lieberman 2012 for a distinction between the two networks in the same study). Technical reasoning is impaired in patients with apraxia of tool use (Osiurak & Rossetti 2017), whereas theory-of-mind disorders are commonly observed in most psychiatric disorders. It is therefore not viable for a neuroscientist to consider that technical reasoning and theory of mind are two manifestations of the same ability.

Another point concerns our discussion on reverse engineering. We focused on the case where an individual knows the function of a tool and has to reason about how it can be used or built (pure reverse engineering). **Hernik** suggests that we might be “right in pointing out the role of naïve mechanical principles in these processes” (p. XX). However, as **Hernik** stresses, we did not elaborate on the opposite case, i.e. where an individual has to infer the conventional function of an artefact (e.g., a hammer) she or he has never seen before (hereafter called teleofunctional inference). As a matter of fact, we have already discussed this aspect and corroborated **Hernik**’s hypothesis that humans might solve teleofunctional inference situations by using a kind of “teleological reasoning” (see Osiurak 2017; Osiurak & Badets 2016; Osiurak et al. 2008). In the case of reverse engineering, individuals know the function (i.e., the goal) of the tool in question.

The task is to infer the potential technical means allowing them to use or make the tool. This task is very close to novel tool-use tasks in which participants have to find out how to use or make novel tools in order to solve mechanical problems (see sect. 2.1). It is not possible to consider that familiar tool-use tasks (e.g., using a hammer with a nail) correspond to reverse engineering because the participants already know the tools. This is why this task is called familiar. Nevertheless, familiar tool-use tasks can become novel tool-use tasks if the individual does not know the tools. This is the case of patients with semantic disorders (e.g., semantic dementia) after damage to the anterior temporal cortex. These patients can be unable to name or describe the conventional use of familiar tools. Interestingly, these patients perform relatively well in novel tool-use tasks, as well as in familiar tool-use tasks, when both the tool and the object are presented (e.g., Baumard et al. 2016; Hodges et al. 2000; Lesourd et al. 2016; Osiurak et al. 2008; Silveri & Ciccarelli 2009). These findings contrast with those obtained in patients with lesions to the left inferior parietal lobe (i.e., the neural basis of technical reasoning), who can be severely impaired on both familiar and novel tool-use tasks (see sect. 2.1). In sum, these findings demonstrate that technical reasoning is critical to reverse engineering.

The question is how these patients with semantic disorders behave when they are presented with a single familiar tool (i.e., teleofunctional inference). In this case, the evidence indicates that they experience great difficulties in demonstrating the conventional use (see Hodges et al. 2000; Osiurak et al. 2008; Sirigu et al. 1991). Nevertheless, their behavior still seems to be driven by their spared technical-reasoning skills, leading them, for instance, to use a screwdriver as a gimlet (see Osiurak et al. 2008). In other words, the degradation of knowledge about the social usages of familiar tools and objects prevents them from performing the “teleological reasoning” highlighted by **Hernik**, but not from making use of technical reasoning in order to find a potential use for the tool, and this search for technical means remains a necessary component of teleofunctional inference. As mentioned above, these patients have lesions to the anterior temporal cortex, a brain area involved in the neural network involved in theory of mind (see above). This explains why they can present theory-of-mind impairments (Duval et al. 2012; Irish et al. 2014). Taken together, these findings extend the discussion initiated by **Hernik**, by suggesting that teleological reasoning might be specifically involved in teleofunctional inference but not in reverse engineering. However, these findings also indicate that technical reasoning remains necessary in both. Therefore, this leads us to assume, contrary to **Hernik**, that the

structure underpinning technical reasoning is critical for the progressive emergence of CTC, even if teleological reasoning (probably based on theory-of-mind skills/functional knowledge) might have helped boost it later during evolution.

Moll et al. also address the question of the role of technical reasoning in teleofunctional inference situations. They reported a small study they conducted, in which they presented participants with an olive/cherry pitter (an artefact also used by Humphreys 2001 to elaborate on his theory of affordances). This is a very unfamiliar tool which is useful for removing stones. They found that only one of the 21 adults they met was able to find the correct conventional use of this tool. For **Moll et al.**, this demonstrates the clear limits of the technical-reasoning hypothesis of CTC and particularly the link we draw between technical reasoning and reverse engineering. Again, as stressed above, this statement seems to be anchored in an omniscient view of technical reasoning which we do not support. However, as rightly stressed by **Hernik**, this is not a proper case of reverse engineering, but rather of teleofunctional inference. Consequently, as discussed immediately above, technical reasoning is not sufficient to infer the conventional use of a tool that an individual has never seen before. Instead, if **Moll et al.** wished to conduct another small study, they could present their participants with a real reverse-engineering condition by asking them how to use this tool with an olive or a cherry, or simply by proposing both the tool and the olive/cherry. In this case, we predict that most of the participants would be able to find the solution.

Motes-Rodrigo et al. hold that we “might be wrong in assuming that [working memory] only allows for storing mechanical actions... [working memory] could allow for combinations of mechanical actions – there might be no need to assume separate technical reasoning skills” (pp. XX; for a similar point, see **Gabora & Smith**). Working memory is commonly defined as a system devoted to allocating a limited pool of attentional resources to the simultaneous maintenance and processing of information (Barrouillet et al. 2011; Plancher & Barrouillet in press). In line with this, we agree with **Motes-Rodrigo et al.** that working memory provides the attentional resources needed for the manipulation of mental representations in the short term. However, contrary to what they argue, working memory does not, strictly speaking, manipulate/process these mental representations. Let us illustrate this point with an example from the technical domain, namely the making of a simple spear. If an individual intends to plan

the full sequence of mechanical actions required to make a simple spear, she or he will face the challenge of solving a series of technical problems. For instance, Problem A is to make something pointed enough to go through the prey. Solution A can be to make a pointed stone. Problem B is to transform a stone into a pointed stone. Solution B is to use a hammerstone, and so on. Note that the generation of some solutions can place constraints on the solutions produced subsequently, or even create new problems (e.g., the shape and size of the shaft of the spear have to be adapted to the point in order to connect them together). As detailed in sect. 2.4, each of these problems is solved through technical reasoning. Working memory is useful here for allocating attentional resources to the maintenance and processing of information (e.g., maintaining Solution A while solving/processing Problem B). The allocation of these resources can quickly become a complex task if the sequence increases and if the different technical problems are interconnected (e.g., solving/processing Problem D, which is based on the maintenance of Solutions A, B, and C). This example clearly illustrates that the role of working memory is not to “manipulate” or “process” information, strictly speaking, but rather to allow other cognitive processes to manipulate information that does not yet exist in the environment. The corollary is that technical reasoning and working memory need to be understood separately because they are based on distinct neurocognitive processes, contrary to what **Motes-Rodrigo et al.** suggest. A significant body of neuropsychological evidence has confirmed that these two cognitive abilities can be impaired independently (for a review, see Osiurak 2014).

As explained in sect. 2.1, our approach is also in line with long-term working-memory models (for a similar view, Wynn & Coolidge 2014), which are very instructive for understanding how expertise can interact with working memory. The challenge for working memory is to allocate attentional resources to both the maintenance and processing of information. In this frame, if less resources are devoted to processing information, then more resources can be assigned to the maintenance of information. Experts are characterized by their ability to process information more quickly in their domain of expertise. The corollary is that an expert, say, in a specific technical domain (e.g., weapon-making) will be able to solve each of the technical problems raised by the making of a simple spear more quickly. Therefore, she or he will have more attentional resources available to maintain the different technical solutions generated and, as a result, be able to progress further in the task and undertake full planning. By contrast, the cost of processing will be higher for a non-expert, leading her or him to have less attentional resources

available for maintenance. The consequence is that she or he will have to engage in partial planning, by progressing in the task based on environmental feedback and trial and error. This is an instance of reasoned trial and error, with behavior being driven by a number of technical solutions generated through technical reasoning (but not all the technical solutions required to complete the task). **Gabora and Smith** stressed that, strictly speaking, trial and error cannot be reasoned. We hope that this clarification will make it easier to understand that trial and error can also be reasoned (see also Vaesen 2012). More importantly, they also claim that our approach to “working memory contradicts decades of research on the psychology of creativity” (pp. XX). We partly disagree with this critique. The interaction of expertise with working memory as described above implies that an expert in a specific domain will be able to manipulate a greater number of items of information in the short term and, thus, generate more suitable and novel ideas than a non-expert. This conception of creativity is perfectly consistent with some work on creativity that has demonstrated that the degree of expertise (i.e., the amount of knowledge) in a specific domain is an important prerequisite for creativity (e.g., Simonton 2000; for further discussion on this aspect, see also [Endnote 7](#)). In other words, our approach to working memory does not contradict the whole body of psychological literature on creativity.

R7. On the origins of the elephant

The culture-gene coevolutionary approach assumes that culture has shaped the human genome by driving the evolution of both our bodies and brains (e.g., Laland et al. 2010). In this approach, the focus has mainly been on the adaptation of social cognitive skills (e.g., see Chudek & Henrich 2011), as also suggested by the cultural niche hypothesis (Boyd et al. 2011), which is akin to this approach. Our approach is consistent with this, although it differs by suggesting that culture (but not CTC) could also have favored the emergence of non-social cognitive skills, such as technical reasoning. We would like to elaborate on this point and this will also give us the opportunity to discuss the idea that our “account is evolutionarily impossible, as it assumes that ancestral hominins must have made a giant cognitive leap to evolve modern technical reasoning skills before cumulative culture could get off the ground. O&R provide no suggestions as to what selective pressures might drive the evolution of technical reasoning in ancestral populations” (**Thornton et al.**; pp. XX).

First of all, we do not consider that culture or any other form of cultural evolution originates in technical reasoning (for a similar viewpoint, see **Claidière**). The technical-reasoning hypothesis of CTC is consistent with the assumption that some specific social conditions (i.e., gregariousness and social tolerance) are the prerequisites for the emergence of social learning and, *a fortiori*, culture (see sect. R2). It is precisely in such a context that technical reasoning, in concert with “simple” forms of social learning, can lead to signs of CTC. This does not imply that all the cognitive components of technical reasoning have evolved spontaneously and that some of them are not shared with other species. Evidence clearly indicates that nonhuman animals can show causal understanding of the physical world (see sect. 2.1). Some specific components, such as the analogical component, could have nevertheless emerged in our human ancestors, making technical reasoning unique to our lineage (i.e., no giant cognitive leap as claimed by **Thornton et al.**). The reason for this emergence does not concern survival, strictly speaking (e.g., see Toth 1985). Instead, these components could have been selected because they conferred an adaptive advantage in terms of food acquisition or protection, putting pressure on the other species (a proposal very similar to the cognitive niche hypothesis)⁴. Paleoneurological work could be done to test whether our human ancestors possessed the parietal structure underlying technical reasoning (i.e., the area PF within the left inferior parietal lobe), as suggested by **Gruber**. In addition, our approach posits that the development of CTC could have generated a technology-rich environment made up of more and more complex and “opaque” tools⁵, which could have favored – among other things (see **Claidière**) – the selection of specific social cognitive skills (i.e., theory of mind) which are useful for increasing social transmission. On this point, the technical-reasoning hypothesis of CTC is in line with the culture-gene approach and the cultural niche hypothesis. Indeed, it also provides a good way to reconcile the cognitive niche and the cultural niche hypothesis: Culture→Non-social cognitive skills (Technical reasoning)→Signs of CTC→Social cognitive skills (Theory of mind)→Complex forms of CTC.

Taylor and Jelbert and **Rutz and Hunt** emphasize that signs of CTC can also be observed in New Caledonian crows, a species known for its causal-understanding skills. A recent study also reported that New Caledonian crows can improve their tool-making behavior by means of situations very close to reverse engineering (Jelbert et al. 2018). However, evidence also shows

that they can benefit from “simple” but not from more complex forms of social learning (Logan et al. 2016). In broad terms, as stressed by these commentators, these findings confirm the idea that signs of CTC can emerge from the interaction between non-social cognitive skills and “simple” forms of social learning, partly corroborating our approach. We say “partly” because they also challenge this. Indeed, one of our key assumptions is that signs of CTC should be observed only in species equipped with technical-reasoning skills, particularly humans. Even if we can elaborate on the fact that New Caledonian crows might not possess all the cognitive components of technical reasoning (notably the analogical component), it remains that these findings imply that CTC may occur even with less elaborate forms of “physical understanding”. Therefore, resolving this discrepancy should lead to some fascinating future research dedicated to exploring this aspect. In the meantime, we have to acknowledge that these findings do not validate some of our predictions.

R8. Is the elephant too micro?

In the target article, we discussed in detail – perhaps too much detail – the results obtained from micro-society experiments and particularly those that used reverse-engineering conditions. We also mentioned that experiments of this kind suffer from the limitation that they do not reflect how technical transmission occurs in everyday life (sect. 5), a limitation also stressed by **O’Brien & Bentley**. We acknowledge that this could have created another mis/overinterpretation of our approach, consisting in thinking that human ancestors could have shown signs of CTC on the basis of reverse engineering alone (for related concerns, see **Derex & Boyd; Thornton et al.**). In fact, the technical-reasoning hypothesis of CTC assumes that human ancestors could have developed CTC on the basis of reverse engineering and other “simple” forms of social learning (e.g., observation). Nevertheless, reverse-engineering conditions are very instructive because they allow us to test without ambiguity whether CTC can emerge without complex social learning. We hope that this clarification will help to correct this mis/overinterpretation.

The methodology employed in all our published studies using micro-society paradigms consisted in performing additional testing to assess certain participants’ cognitive skills in order to link them to the performance reported in the chains (e.g., Osiurak et al. 2016). This methodology was

informative in indicating that learners' technical-reasoning skills are systematically the better predictor of cumulative performance, a key finding for our approach. We also assessed theory-of-mind skills by using two tasks, namely, the Comic Strip task and the Reading-the-Mind-in-the Eyes task. **Weinstein and Baldwin** argue that this methodological choice can explain why we did not find any link between theory-of-mind skills and cumulative performance in our micro-society experiments. We agree that theory of mind is a complex cognitive ability with many different facets (Quesque & Rossetti in press). We also appreciate **Weinstein and Baldwin's** argument that an absence of a statistical link between cumulative performance and theory-of-mind skills as assessed with these two tasks does not imply that this link does not exist, particularly if these tasks are not appropriate for assessing theory of mind. Nevertheless, an important finding is that we obtained such a link in a communication condition in which the participants sat on two chairs back-to-back so that they could only communicate verbally (Osiurak et al. 2020). As detailed in sect. 3.3, our approach specifically predicts this link in this condition. In broad terms, this result provides strong support for our approach and also confirms that our methodological choice was appropriate. It should also be noted that, as pointed out by **Weinstein and Baldwin**, we know that the Reading-the-Mind-in-the Eyes task can be subject to ceiling effects. This explains why we proposed a modified version with a time limit of 3 minutes, allowing us to obtain very sensitive measures even with a population of undergraduate students.

R9. Elephant...action!

The technical-reasoning hypothesis was initially developed in the field of neuropsychology to account for tool-use disorders observed in apraxic patients. This hypothesis is an alternative to the long-standing hypothesis that tool use is only based on specific tool-use motor programs (see sect. 2.1). This has generated an intense debate in the field, which has led us to discuss in more detail the interaction between technical reasoning and the motor-control system. Some commentaries echo this debate (**Houkes & Vaesen; Lockman, Tamis-LeMonda, & Adolph [Lockman et al.]; Motes-Rodrigo et al.; Robertson**).

The technical-reasoning hypothesis assumes that technical reasoning and the motor-control system are orthogonal processes which have evolved to solve distinct problems. The former generates potential mechanical actions in order to solve technical problems. The latter selects the

most appropriate motor actions in order to realize the mechanical actions generated through technical reasoning⁶. Therefore, technical reasoning is concerned with the understanding of *mechanical actions*, whereas the motor-control system is concerned with the perception of *affordances* (Osiurak et al. 2010, 2017; Osiurak & Badets 2016). We define affordances as animal-relative biomechanical properties specifying action possibilities within a body-centered frame of reference (Osiurak et al. 2017). Affordances differ from mechanical actions because mechanical actions are not body-centered but environment-centered. It is one thing to perceive that a knife is *grasp-able* (i.e., a relationship between the biomechanical property of a given individual and an environmental object) and another to understand that this knife can be useful to cut a tomato (i.e., a relationship between the physical properties of the knife and the tomato). **Lockman et al.** state that our description of the motor-control system places exaggerated emphasis on the “executive component” of this system and neglects the “explorative component”. We strongly agree with this statement in that the motor-control system can also be involved in the exploration of the physical world in order to extract information useful for both the perception of affordances and the understanding of mechanical actions. We recently elaborated in more detail on this point (Osiurak et al. in press).

Robertson holds that our approach needs compelling evidence in order to demonstrate that mechanical knowledge is not a “dispositional competence” but a kind of “conceptual, propositional knowledge”. For him, we “over-intellectualize” the cognitive activity involved in skilled tool practices. **Robertson**’s approach seems to be anchored in an embodied cognition view, as illustrated by his reference to procedural knowledge, a concept close to that of tool-use motor programs. His view is relatively consistent – perhaps paradoxically – with the classical distinction between declarative memory and procedural memory, which implies that knowledge is necessarily declarative or “propositional”. The fact is that we have never stated that mechanical knowledge is declarative or propositional (sect. 2.1). It is a specific form of knowledge based on an implicit understanding of the physical world which is difficult to make explicit. The corollary is that mechanical knowledge is also not a kind of procedural knowledge based on sensorimotor information as suggested by **Robertson**. We have already gathered a large body of evidence in favor of this view (for reviews, e.g., Osiurak & Badets 2016; Osiurak & Heinke 2018). One of our most compelling arguments is that apraxic patients with tool-use disorders can be impaired not only when asked to use familiar tools, but also when they have to

use or make novel tools to solve mechanical problems (see sect. 2.1 and Figure 2). This finding cannot be interpreted as a deficit of “procedural knowledge” or “tool-use motor programs” because the impairment concerns both the selection of appropriate tools and the realization of the appropriate mechanical action. In other words, the evidence seems to contradict the “under”-intellectualized approach to tool use advocated by **Robertson**.

In the target article, we presented evidence indicating that imitation is not unique to humans and can also be observed in “two-action” paradigms proposed to nonhumans such as chimpanzees (e.g., Horner et al., 2006). **Motes-Rodrigo et al.** claim that these studies do not really demonstrate that chimpanzees can imitate. For instance, they cite the study of Tennie et al. (2010) who presented chimpanzees with a floating peanut task in three conditions. In the full-model condition, chimpanzees could observe a conspecific solving the task by spitting water into the tube. In the “emulation” condition, a human experimenter poured water into the tube. In the baseline condition, there was no demonstration. They found that chimpanzees in the full-model and “emulation” conditions outperformed those in the baseline condition. However, no difference was reported between these two experimental conditions. Although these findings are interesting, they are unfortunately based on a null result. We acknowledge that this null result nevertheless questions the idea that imitation can be found in nonhumans. Nevertheless, as discussed in sect. 2.4, it appears more viable theoretically to explore imitative skills by placing the focus on the mechanical level instead of the motor level, as proposed in the “two-action” paradigm.

R10. Conclusion

Like any theory, the approach developed in the target article is necessarily incomplete, and, as all scientists are, we are well aware of this. Theories are attempts to organize a collection of findings in a coherent way in order to offer a satisfying answer to a question, until another theory provides a more satisfying one. Our theoretical approach is no more and no less than such an attempt. In this regard, we are also aware of some points raised by commentators that pose a great challenge to our approach. We agree that our approach to human cultural evolution is too narrow. We focused on cumulative *technological* culture, whereas human culture is not only technological, but also, for instance, mathematical, artistic or linguistic (**Miu et al.**; **Thornton et**

al.; Whiten). Of course, we made it clear that our scope was limited to this specific domain. Nevertheless, this limitation could have led us to ignore important aspects that could deeply change our approach. Further work is needed to determine whether this is the case.

We also acknowledge that some findings do not confirm our key assumptions, such as the presence of signs of CTC in New Caledonian crows (sect. R7; **Rutz & Hunt; Taylor & Jelbert**). Other commentators have also stressed that nonhumans might possess cognitive components of technical reasoning (e.g., transfer skills), contrary to what we have assumed (**Boesch; Whiten**). In this respect, we agree that our theoretical approach needs additional attention in order to determine whether these findings clearly contradict it. **Whiten** raised the question of why chimpanzees do not show overimitation in the same way that children or adults do, a finding that could rule out the idea that humans alone possess technical-reasoning skills (see also **Thornton et al.**). As explained in sect. 4.4, this phenomenon seems to be reported only when children interact with adults, but not with other children. In other words, it is not inconsistent with the idea that children could already possess a certain level of technical reasoning allowing them to detect what is or is not relevant (according to their own level of mechanical knowledge) in the mechanical actions observed. Nevertheless, the development of metacognitive/theory-of-mind skills could lead them to “blanket-copy” individuals who appear to them as more reliable sources⁷. Regardless, we agree that empirical effort is needed here to explore this possibility.

To conclude, we would like to address **Boesch**'s skepticism toward the scientific nature of our approach. What is science? Science does not consist in collecting evidence. This is due to the simple fact that there is no evidence, strictly speaking, but only interpretations of what might constitute evidence. In this context, advances can also come from understanding how scientists think and interpret data in order to overcome epistemological obstacles. **Boesch**'s commentary is instructive in this way because he seems to impute incorrect motives to our approach. We did not assume that humans are *superior* by suggesting that they might possess *unique* non-social cognitive skills. Considering that, say, dolphins or birds possess unique adaptations to hydrodynamical or aerodynamical constraints does not amount to considering that dolphins or birds are superior. We are not ideological, and we did not perpetuate “the simple trick to make humans look superior” (pp. **XX**; **Boesch**), because, quite simply, we do not view human

cognition as superior. Instead, our approach is scientific because it provides an original framework which is intended to overcome a potential epistemological obstacle that consists in thinking that CTC necessarily originates in social cognitive skills. We are convinced that such an alternative approach can be fruitful in providing a reinterpretation of the data collected on the topic. We have already discussed this viewpoint in the different rounds of reviewing we went through with **Boesch** before publishing our target article. Regardless, this commentary nicely illustrates that CTC is a fascinating phenomenon that needs much more discussion in order to reconcile the different viewpoints without, nevertheless, imputing incorrect motives to other researchers.

Endnotes

¹ We acknowledge that we did not mention these important prerequisites in the target article, which could have led some commentators to misinterpret our approach.

² The concept of strategy implies that the decision is made by the individual and not imposed by the environment. For instance, in the context of CTC, this would consist in opting for social learning instead of asocial learning. **Derex and Boyd** claim that individuals have to follow such strategies to allocate their time and effort efficiently. To support their claim, they cited the study of Beck et al. (2011), which demonstrated that children can experience difficulties in acquiring a tool-making technique by themselves, but not after social demonstration. The question is whether this study really supports their claim. In this study, the children *did not decide* to follow the social demonstration instead of addressing the problem themselves. The social demonstration was imposed by the experimenter.

³ **Miu et al.** pointed out that CTC changes the nature of the technical problems that must be solved, thereby opening up new niches with new technical problems. We fully agree with them and would like to add that this also helps increase the number of techniques discovered and, as a result, reduces the possibility that an individual may, in her or his lifetime, master all the techniques of a given domain and, even less so, multiple domains.

⁴ As mentioned in sect. 5, we adopted a Lorenzian view in assuming that our “motivation” to solve technical problems comes first and foremost from the very ability to solve technical problems. Therefore, even if the pride hypothesis developed by **Tracy** is very original, allowing us to build an interesting bridge with the social-learning strategies discussed in sect. 4, this hypothesis cannot explain the origins of human materiality *stricto sensu*.

⁵ **Gruber** discusses several studies reporting the acquisition of “opaque” tool-making through social learning in nonhuman primates (e.g., Gruber et al. 2009). According to him, these findings contradict the idea that opacity is the key driver of CTC in humans as suggested by Csibra & Gergely (2009) and, to a lesser extent, by our approach. It is true that we posited that the complexification of tools and their increasing opacity could have favored the emergence of theory-of-mind skills in human ancestors, thereby facilitating social transmission, a perspective

similar to that of Csibra and Gergely (2009). However, this implies that the tool repertoire is relatively large and also includes many “opaque” tools. In other words, the observation of some instances of opaque tools acquired through social learning does not contradict our approach.

⁶In this framework, performing, for instance, a “rotating” motor action to use a screwdriver does not imply that the “rotating” mechanical action involving the screwdriver is not “too far above the level of motor action” (pp. XX; Houkes & Vaesen). This tool-use situation makes it necessary to solve two distinct problems, the first being to determine how to drive the screw with the screwdriver (technical reasoning) and the second to determine which motor action is the most appropriate to do so (motor-control system). Simply, the fact that the realization of the mechanical action imposes a motor action that is very similar can create the illusion that the knowledge of how to use a screwdriver is sensorimotor or procedural.

⁷In a way, the interaction described here between technical-reasoning and theory-of-mind skills is consistent with the mechanistic *versus* mentalistic cognition distinction proposed by Crespi.

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