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Technition: When Tools Come Out Of The Closet

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Abstract

People are ambivalently enthusiastic and anxious about how far technology can go. Therefore, understanding the neurocognitive bases of the human technical mind should be a major topic of cognitive sciences. Yet, surprisingly, scientists are not interested in that topic or address it marginally in other mainstream domains (e.g., motor control, action observation, social cognition). As a matter of fact, this may hinder our understanding of the necessary neurocognitive skills underlying our appetite for transforming our physical environment. Here, we develop the thesis that our technical mind originates in perhaps uniquely human neurocognitive skills, namely, technical-reasoning skills involving the area PF within the left inferior parietal lobe. This thesis creates an epistemological rupture with the state-of-the-art, justifying the emergence of a new field in cognitive sciences (i.e., *Technition*) dedicated to the intelligence hidden behind tools and other forms of technologies including constructions.

Keywords: Tool Use; Cumulative Technological Culture; Action Observation; Motor Control.

Cinderella

Scientists need eloquence and pedagogy, but much less often technical skills. The “research-is-me-search” proverb may be trivial. We agree, but when applied to cognitive sciences, it reflects a certain reality, since much more scientists have assumed the human uniqueness of language and **theory-of-mind** skills (see **Table 1** for definition of bold words) than of technical skills. This lack of interest is evidenced in cognitive sciences by the absence of any specialized journal on the topic or chapters in renowned handbooks¹. This is surprising inasmuch as our technical skills have been of the greatest importance for the evolutionary success of our ancestors. The corollary is that technical skills are addressed marginally in other mainstream domains (e.g., motor control, action observation, social cognition), which may hinder our understanding of the necessary neurocognitive skills allowing us to deeply modify the surface of the Earth? Here we propose to follow another direction by calling for a new field in cognitive sciences focusing on our technical skills and labeled *Technition*. This call is motivated by recent psychological and neuroimaging evidence, indicating that our technical skills might originate in perhaps uniquely human neurocognitive skills, namely, **technical-reasoning** skills, involving the area PF within the left inferior parietal lobe. Based on this, we argue that the study of our technical skills deserves a field in its own right, which could help researchers to organize their findings around key issues and lead us to better understand how we significantly transform our physical environment by **using tools**, but also by **making them** or building **constructions**. We shall begin our journey to Technition with a brief presentation of the state-of-the-art.

< Insert **Table 1** about here >

The contemporary story

How our brain manages to use tools is a story that can be easily told based on findings from cognitive sciences. In that story (hereafter called the contemporary story), the main character is the human hand, namely, the most dexterous end-effector of the animal kingdom (Ambrose, 2001; Vaesen, 2012). Its control requires dorsal brain areas particularly within the parietal lobe, originating from a preexisting primate prehension system (also called **motor-control system**; Fagg & Arbib, 1998; Wolpert, 1997). Given that human tool use goes beyond from what is known in other species including tool-using ones, the key assumption is that this prehension system has evolved over time, allowing us to store specific motor programs mainly within the left inferior parietal lobe (Buxbaum & Kalénine, 2010; Buxbaum, Shapiro, & Coslett, 2015; Daprati & Sirigu, 2006; Johnson-Frey, 2004; Heilman, Rothi, & Valenstein, 1982; Poizner et al., 1995; van Elk, van Schie, & Bekkering, 2014). These programs contain information about the postural and kinematic components of hand movements during the use of a tool (hereafter called **manipulation knowledge**), thereby providing internal models (i.e., a visuokinesthetic representation of the movement) that are critical to guide hand movements (Buxbaum, 2017). These internal models can be learned by observing conspecifics, through a motor resonance mechanism: Watching someone else execute tool-use hand movements offers a kind of “external” model that can be later internalized and reused for subsequent actions (Buxbaum, 2017; Stout & Hecht, 2017). This basic mechanism could be the foundation for social transmission and development of tool use and making in early Paleolithic skills (Harmand et al., 2015), namely, an important turning point in prehistory marking the onset of **cumulative technological culture** (Boyd & Richerson, 1985; Tomasello, Kruger, & Ratner, 1993). Here is where the contemporary story ends

since so-called higher-level cognitive processes (i.e., theory-of-mind and language skills) might be necessary to support the transmission of social information with greater fidelity notably when technology becomes more and more complex (Boyd & Richerson, 1985; Dean, Kendal, Schapiro, Thierry, & Laland, 2012; Hermann, Call, Hernández-Lloreda, Hare, & Moll, 2007; Stout & Hecht, 2017; Tomasello, Carpenter, Call, Behne, & Moll, 2005; Tomasello et al., 1993). We guess you know this story. What if we told you another story?

The basic question

Rewriting a story needs much more than simply revising some chapters. The starting point has also to be reconsidered. This is also true for science, where significant advances have always arisen not because of the generation of new solutions but rather of a new way of conceiving the basic question. So, what could be that question? The contemporary story offers us a particular focus on how humans control their hands when using tools (i.e., hand-tool relationships). This is a valuable purpose, helping us to develop original experimental paradigms to explore how humans manipulate tools. Nevertheless, the control of the hand is only one aspect of what characterizes human tool use, which is specific at several regards (Osiurak, 2017). We do not only use **simple tools**, like most of tool-using species, but also **complex tools** that transform our motor energy into distinctively mechanical energy (Frey, 2007). We are also alone in using “natural” forces (e.g., wind, fire, water; Shumaker, Walkup, & Beck, 2011)² and showing **prospective diagnostic** (Povinelli & Frey, 2016) and **transfer** skills (Osiurak, Jarry, & Le Gall, 2010; Penn, Holyoak, & Povinelli, 2008; Penn & Povinelli, 2007), which have allowed us to do incredible things, such as communicating with peers at the other end of the Earth or travelling through space. The contemporary story describes how the brain

links a hand movement with a specific tool (i.e., hand-tool relationship), leaving open the issue of our understanding of tool-object relationships and, as a result, how we can (1) master and invent mechanical actions that are not natural for us (i.e., complex tool use, natural forces), (2) predict mechanical actions between two external objects or tools (i.e., prospective diagnosis), or (3) transfer what we have learned in a situation to another one (i.e., transfer skills; Osiurak & Badets, 2016). Actually, the contemporary story is not well equipped to explain how we can use novel tools or perform effective tool selection based on physical object properties, again because of its focus on hand-tool relationships. Very similar limitations can be addressed for social transmission. It remains difficult to understand how motor resonance can be enough to help an observer learn the physical relationship between the tools and objects involved in the task or to transfer and adapt what is learnt from the social situation to other situations lived individually (e.g., learning by observation to make a trap for frogs and then adapting it for rabbits; Vaesen, 2012).

These considerations lead us to offer an alternative that goes beyond the epistemological idea that humans are *manipulators*, which reduces the focus on the motor-control issue (**Box 1**). This alternative is grounded on the assumption that humans are *physical problem-solvers* or *makers*. In this context, the basic problem of human tool use is as follows:

What are the neurocognitive bases of our appetite for transforming our physical environment?

Viewing humans as makers may seem surprising given that, in modern societies, humans rarely have to make tools in the strict sense, by performing detaching, subtracting, adding or reshaping actions (Shumaker et al., 2011). However, if you take a minute to remember your day, you should more easily realize that we use tools to solve

physical problems. As soon as we awake and intend to prepare breakfast, we have problems to be solved (e.g., to obtain a slice of bread). To solve them, we have to mentally make the mechanical action (e.g., cutting, that is, an action involving something sharp and rigid enough relatively to a target object) and to select the appropriate tool based on the physical constraint of the task (i.e., something sharp and rigid enough relatively to *bread*). If we assume that even a so-called familiar activity such as preparing breakfast is a problem-solving situation requiring mental making, it becomes easier to consider that the same cognitive process can be at work whatever the familiarity of the task: Novel tool use, unusual use of familiar tools, or even the physical making of a tool or a construction (see sect. “The opacity” for the specific case of use of “opaque” tools). It becomes also easier to imagine a common field of research investigating how modern humans but also early hominins were able to use and make tools (e.g., how to make a spear with a split-based bone point; Haidle, 2010). In this regard, the term tool may be too reductive, leading us to place exaggerated emphasis on a particular category of behavior, namely, tool use – and also indirectly on manipulation. Therefore, even if we will use instances of tool use to illustrate our purpose, the thesis defended here is that the same rationale can be applied to tool making or construction, which reflect even better the potential of our technical mind.

< Insert **Box 1** about here >

The illusion

At this point, an important epistemological question is to understand why the *humans-are-manipulators* illusion, one of the key assumptions of the contemporary story, is so widely accepted in the literature (see also **Box 1**). Two main epistemological biases can explain this illusion. The first is to consider that routine activities necessarily

reflect the involvement of automatic processes (for a discussion, see Osiurak, 2014; see also Goldenberg, 2013). It is true that we use many tools and objects in everyday life. Very frequently, we even use the same tools and objects each day and in the same context (e.g., preparing breakfast). This leads proponents of the contemporary story to assume that the routine nature of our tool-use activities can be supported by the automatic activation of manipulation knowledge (e.g., Rothi et al. 1991; for a similar view, see Cooper, 2002; Cooper & Shallice, 2000, 2006). Yet, a routine activity does not necessarily imply that automatic or low-level cognitive processes are at work. After all, we generate an incredible number of sentences everyday. However, language skills because of their routine nature cannot be reduced to the retrieval of bucco-oral motor programs. As a matter of fact, these routine activities reveal the existence of a certain level of expertise, leading humans to carry out high-level cognitive processes more and more quickly. The thesis defended here is that even if tool-use activities may appear to us as routines, most of them are based on the expertise we have in reasoning about our physical world (for further discussion about the link between technical reasoning and routine tool-use activities, see Osiurak, 2014).

The second limitation concerns the experimental paradigms that are sometimes employed to investigate tool use, which exaggerate the role played by manipulation. We can illustrate this with an example of stimulus-response compatibility paradigm initially introduced by Tucker and Ellis (1998). In this paradigm, participants are presented with pictures of tools with the handle oriented to the right versus to the left. The task can be, for instance, to determine the vertical orientation of the tool (i.e., upright/inverted) by pressing a right key versus a left key. Although the orientation of the handle is irrelevant to the task itself, an orientation effect can occur: Participants are faster to respond with a right key press when the handle is oriented to the right and vice versa for the left key

press. These findings have been widely cited to argue in favor of the automatic activation of motor programs associated to the use of tools³ (see Osiurak & Badets, 2016). This paradigm is a good illustration of the experiments largely employed to generate cognitive models of tool use, where the focus is clearly placed on manipulation. Indeed, surprisingly, participants are not asked to actually use tools, as if the investigation of tool use did not require exploring how humans really transform their physical world. In addition, this kind of paradigm tends to orient scientists' attention to the "manipulation moment", leading to overlook what happens before or during the activity. The stimuli – mostly pictures of tools – are artificial situations corresponding to a workspace in which tools and objects are already ready to be manipulated. Participants have not to select and get the tools needed. By contrast, when we engage in everyday activities such as when preparing breakfast, all the needed tools and objects are not directly at hand in the workplace. They can be stored in cupboards or drawers, so we are forced to get them either before or during the activity. We can also hesitate between two knives depending on the quality of bread. Sometimes, we also have to modify our tool choice because the mechanical action intended does not work. As a matter of fact, the manipulation moment occurs only after these cognitive tasks. So, to be effective, any theoretical framework of tool use must take into account this "preparation moment", which reflects our understanding of the physical world. Otherwise, the risk is to generate cognitive models that contribute to the illusion that tool use is only a matter of manipulation because only the motor component is considered. In addition, taking into account this preparation moment in tool-use activities can also help us to create models that include other manifestations of our technical mind, such as tool making or construction, in which this preparation moment is much more patent.

The missing character

If humans use tools to solve physical problems in daily life, the next issue is how do we do so? The idea that humans could possess knowledge about the physical world or specific skills to generate causal relationships within it has already been addressed through the concepts of naïve/intuitive physics (McCloskey, 1983), mechanical reasoning (Hegarty, 2004) or causal reasoning, and even in old writings such as those of William James (1890/2007). Nevertheless, it is only very recently that this idea has been clearly extended to the field of tool use with the concept of technical reasoning (Goldenberg & Hagmann, 1998; Orban & Caruana, 2014; Osiurak, 2014; Osiurak & Badets, 2016; Osiurak et al., 2009, 2010; see **Figure 1**). The core assumption is that this reasoning is based on **mechanical knowledge**, which contains non-declarative (**Box 1**), abstract information about physical principles and mechanical actions (e.g., cutting, lever, support)⁴. When a physical problem is detected, we start to reason with mechanical knowledge offering us potential technical solutions. The corollary is that this reasoning is causal because we can foresee the potential outcomes of mechanical actions on the environment (i.e., prospective diagnosis). It is also analogical because of the abstract nature of mechanical knowledge allowing us to transfer what we understood in one situation to another (i.e., transfer skills). When using this reasoning, we identify in the present situation – or from memory – the physical properties of tools and objects that can be exploited to perform the mechanical action generated mentally. In this respect, technical reasoning is not thought to explain only how we use tools, but also how we make them physically or build construction. This reasoning ends with the generation of a mental image of the mechanical action to be performed with tools and objects. Then, this mental image biases the selection of appropriate hand movements via

a motor simulation mechanism within the preexisting primate prehension system – or more generally within the motor-control system, notably if effectors other than the hand are used to perform the motor action intended (Osiurak, Lesourd, Delporte, & Rossetti, 2018).

< Insert **Figure 1** about here >

The evidence

Most of our understanding about tool-use skills, particularly the key role of the left hemisphere, has come from patients with difficulties to use everyday, familiar tools (i.e., **apraxia of tool use**; Osiurak & Rossetti, 2017). The difficulties concern not only the mechanical action performed (e.g., rubbing a hammer on a nail instead of using it to pound the nail) but also the selection of the appropriate tool. The manipulation-knowledge hypothesis has long been the only hypothesis to investigate these difficulties. Yet, it is not really well equipped to do so because of the focus on hand-tool relationships that cannot account for tool selection disorders (i.e., tool-object relationships; see above). Two decades ago, Goldenberg and Hagmann (1998) initiated a series of studies on the ability of left brain-damaged patients to use novel tools to solve mechanical problems. They found that the ability to use both familiar and novel tools was strongly correlated, a finding that has been since widely replicated even in tasks wherein patients have to make novel tools (Bartolo, Daümuller, Della Sala, & Goldenberg, 2007; Goldenberg, Hartmann-Schmid, Sürer, Daümuller, & Hermsdörfer, 2007; Hartmann, Goldenberg, Daümuller, & Hermsdörfer, 2005; Heilman, Maher, Greenwald, & Rothi, 1997; Jarry et al., 2013; Osiurak et al., 2009; **Figure 2a**). These findings have supported the idea that a common cognitive process, namely technical reasoning, is involved in the understanding of tool-object relationships allowing humans

to select relevant tools and perform appropriate mechanical actions, as required in familiar tool use, and novel tool use and making. Further neuropsychological evidence has indicated that the left inferior parietal lobe and particularly the area PF could be the neural basis of this process (Goldenberg & Spatt, 2009; Martin et al., 2016; Salazar-Lopez, Schwaiger, & Hermsdörfer, 2016; **Figure 2b**).

< Insert **Figure 2** about here >

A more direct examination of the predictions derived from the technical-reasoning hypothesis versus the manipulation-knowledge hypothesis was recently made based on a meta-analysis of neuroimaging studies (Reynaud, Lesourd, Navarro, & Osiurak, 2016) in which healthy participants had to focus either on hand-tool relationships (e.g., judging whether a hand posture is correct or not to grasp a tool) or tool-object relationships (e.g., judging whether the mechanical action shown is correct or not). The key divergent prediction concerned the involvement of the left inferior parietal lobe, namely, hand-tool relationships for manipulation knowledge versus tool-object relationships for technical reasoning. As shown in **Figure 2c**, the finding indicates a preferential activation for the left inferior parietal lobe and particularly PF for tasks involving tool-object relationships, confirming the prediction made from the technical-reasoning hypothesis. Activation was also observed within the intraparietal sulcus for hand-tool relationships, which can be explained by motor simulation as suggested, again, by the technical-reasoning hypothesis (see just below).

The manipulation

The role of the motor-control system is to select and plan the most economical motor actions to perform an action based on the individual's biomechanical constraints. According to the technical-reasoning hypothesis, this system is blind to the goal of the

action (e.g., tool use, object transport; see Osiurak & Badets, 2017). If someone intends to use a hammer to pound a nail, the motor-control system will attempt to select the most economical motor actions allowing the individual to realize the mechanical action generated via technical reasoning. Likewise, if the goal is to move an object from one location to another, this system will select the most economical motor actions for achieving this goal. In broad terms, this system is not concerned by the reasons why an individual comes up with the idea of “moving” a particular tool or object in space. It simply attempts to solve how to do so in the most economical way at a biomechanical level. Importantly, this is not to deny that tool use – but, again, the same rationale can be applied to tool making or construction – generates additional problems for the motor-control system compared to object transport or object grasping. During tool-use activities, the main challenge is to control the motion of the tool held according to the position of the object (Lockman, 2000)⁵. The acquisition of such dexterous object-object manipulation is not an easy task, and the motor-control system is certainly not innately equipped for it. The corollary is that this acquisition occurs through exploratory patterns and trial-and-error manipulation (Lockman, 2000). For instance, infants show great within-subject variability in the way of holding a spoon, before they begin to use a specific kind of grip predominantly early in the second year (Connolly & Dalglish, 1993; for similar results for writing, see Greer & Lockman, 1998). These exploratory patterns have also been observed in nonhuman users, such as in wild bearded capuchin monkeys in the context of nut-cracking (Mangalam & Fragaszy, 2015) or New-Caledonian crows in the context of twig tool use (Kenward, Rutz, Weir, & Kacelnik, 2006). In other words, it seems that all tool-using species’ motor-control systems might face the challenge posed by object-object manipulation. However, in at least the particular case of humans, this motor-centered adaptation might occur in parallel to the development of technical-

reasoning skills⁶. Interestingly, recent neuroscience studies on tool use have found that, in humans, the anterior portion of the left supramarginal gyrus within the left inferior parietal lobe might bias signals to the intraparietal sulcus (the brain area underlying the motor-control system) to favor the selection of the motor action that best suits the mechanical action generated via technical reasoning (for a review, see Orban & Caruana, 2014). These findings offer a promising neurocognitive framework in order to better understand the interactions between the motor-control system and technical reasoning **(Figure 1)**.

The others

Observing others interacting with tools and objects provides a rich source of information, avoiding reinventing systematically the wheel. Two sources of information can be identified. The first concerns the motor actions (i.e., hand-tool relationships) performed by the model. The contemporary story posits that this is the critical source of information: Humans learn how to use – or rather manipulate – tools by acquiring information about motor actions performed by their conspecifics, through a motor resonance mechanism (Buxbaum, 2017; Stout & Hecht, 2017). The second source of information, which is subsidiary for the contemporary story, concerns the mechanical action observed (i.e., tool-object relationship). As discussed above, evidence has indicated that technical-reasoning skills are critical for using and making tools in an asocial context. So, the principle of parsimony leads us to predict that these skills also contribute to extracting information about mechanical actions observed in an observational tool-use context. In other words, we reason at a technical level not only when we are engaged in our own tool-use activities, but also when watching others using tools. This alternative may appear at odds with neuroimaging findings that have

indicated that the brain areas underlying the motor-control system (i.e., the intraparietal sulcus particularly) are activated when observing others performing tool-use actions (e.g., Grosbras & Paus, 2006). However, the technical-reasoning hypothesis offers another interpretation of these findings. When someone observes a model performing tool-use actions, she or he reasons about the mechanical actions carried out or just about to be carried out. In an asocial context, motor simulation is needed to select and plan the appropriate motor actions enabling to make concrete the mechanical action generated through technical reasoning. We assume that the same process is at work in the observational context. The observer also engages in motor simulation to plan and select the potential motor actions that she or he could execute in order to carry out the mechanical actions observed or just about to be observed. The corollary is that the brain areas underlying the motor-control system can also be activated when observing others using tools. Nevertheless, this activation does not mirror the motor actions performed by the model but derives indirectly from the mechanical action observed⁷. At a neurocognitive level, this hypothesis can be easily tested because it implies that the observation of tool-use actions should preferentially activate the areas dedicated to technical reasoning – i.e., left inferior parietal lobe and particularly the area PF – as compared to the observation of non-tool-use actions. Interestingly, we recently confirmed this prediction based on a meta-analysis on neuroimaging studies (Reynaud, Navarro, Lesourd, & Osiurak, in press; **Figure 2d**). This finding corroborates previous behavioral results on action imitation indicating that people focus on the mechanical action rather than on the hand movements executed by the demonstrator (Massen & Prinz, 2007a, 2007b, 2009).

The mind of others

The contemporary story ends when more complex technology has to be transmitted socially through theory-of-mind and language skills (see above). The introduction of the perhaps critical, though missing, character – technical reasoning – can deeply modify this story. Cumulative technological culture – a perhaps uniquely human trait – is driven by two engines (Legare & Nielsen, 2015), namely, **imitation** (i.e., copying the behavior with a high fidelity) and **innovation** (i.e., improving the behavior). To date, the focus has been mainly placed on the imitative component (Boyd & Richerson, 1985; Henrich & Gil-White, 2001; Tomasello et al., 1993, 2005). Indeed, faithful social transmission can work as a ratchet to prevent slippage backward, thereby allowing the subsequent improvement of technical solutions. In this line, it has been assumed that imitation could be facilitated in humans because of their unique pedagogical skills originating in theory-of-mind skills (Boyd & Richerson, 1985; Dean et al., 2012; Herrmann et al., 2007; Tomasello et al., 1993, 2005). Said differently, humans imitate because their theory-of-mind skills enable them to form a representation of what their conspecifics understand about a given task. Thus, the teacher can orient the attention of the learner toward relevant information as well as provide appropriate feedback during the task (Dunstone & Caldwell, 2018). This dominant view (i.e., the causal relationship “theory of mind→imitation→cumulative technological culture) has been challenged by a series of studies that has indicated that nonhumans can show imitation in reproducing the same (mechanical) action as the one performed by a model as well as to establish this behavioral pattern as a tradition within their group (Bonnie, Horner, Whiten, & de Waal, 2006; Whiten, Horner, & de Waal, 2005). Therefore,

imitation is not unique to our species and can be observed in species that do not show cumulative technological culture.

Evidence against the theory-of-mind hypothesis of cumulative technological culture also comes from experimental studies using **micro-society paradigms**. According to this hypothesis, cumulative performance should be found only when the teacher and the learner can have face-to-face interactions to exchange information such as for instance in communication conditions. Yet, it has been shown that cumulative performance also emerges in reverse-engineering conditions (Caldwell & Millen, 2009; Caldwell, Renner, & Atkinson, 2018; Zwirner & Thornton, 2015) and, to a lesser extent, in observation conditions in which verbal communication is not permitted (Caldwell & Millen, 2008, 2009; De Oliveira, Reynaud, & Osiurak, 2019; Osiurak et al., 2016). Based on these findings, scientists have reconsidered the key role of learners' causal reasoning (Osiurak & Reynaud, in press; Osiurak et al., 2016; Zwirner & Thornton, 2015; but see also Pinker, 2010; Vaesen, 2012), a perspective close to the technical-reasoning hypothesis of tool-use action observation (see above). In other words, technical-reasoning skills might help the learner to extract relevant information from either the end-product itself or teacher's demonstration/advice in order to reproduce the end-product (i.e., imitation) but also to detect irrelevant information in order to improve the end-product (i.e., innovation). This offers a parsimonious way to explain not only how people copy their predecessors' technologies but also improve them (i.e., imitation and innovation: the dual engines of cumulative technological culture). In addition, the technical-reasoning hypothesis does not deny the importance of social learning, which is a catalyst far more effective than asocial learning to obtain new technical information. Rather, this hypothesis stresses that technical reasoning is an appropriate candidate to

explain how humans can extract technical information in both asocial and social situations (Osiurak & Reynaud, in press).

Although these findings have stressed the key role of technical reasoning in cumulative technological culture, they do not rule out the importance of theory-of-mind skills in at least two specific contexts. The first concerns the making of an opaque end-product. In this case, the **opacity** of the end-product might prevent the learner from understanding the making process (Morgan et al., 2015; Osiurak, 2017; Stout & Hecht, 2017; Wasielewski, 2014). Therefore, teachers' theory-of-mind skills might be critical to provide the learner with information that is not available by merely scrutinizing the end-product (for a similar viewpoint, see Gergely & Csibra, 2006). The second concerns the amount of visual information available to the teacher. This corresponds to pure verbal communication conditions, in which the teacher transmits information about how to build an end-product while nothing is present. Those situations demand a high level of pedagogy, because the teacher needs to form an accurate representation of what the learner knows about the building process in order to guide her or him along this process only with her or his words. We recently tested this prediction in a series of studies using micro-society paradigms (De Oliveira et al., 2019; Osiurak, De Oliveira, Navarro, & Reynaud, in press; Osiurak et al., 2016, in revision). The task was either to build as high as possible a tower with metal wires or a paper airplane that would fly as far as possible. In these studies, participants completed the task as a member of a chain of 10 participants, each of whom performed the task one after the other. There were several experimental conditions: Observation (no communication permitted), communication (verbal exchange and the teacher could observe what the learner was doing) and "pure communication" (the teacher could communicate with the learner but could not see what she or he was doing; i.e., the nothing-is-present situation described

just above). Participants' technical-reasoning and theory-of-mind skills were also measured in additional testing sessions. Results have revealed that the best predictor of cumulative performance was learners' technical-reasoning skills whatever the condition studied. This first key finding confirms the key role of technical reasoning in cumulative technological culture. We also found that teachers' theory-of-mind skills also predicted cumulative performance but only in the pure communication condition. This second key finding corroborates the interpretation offered above about the potential role of theory of mind in this phenomenon.

To sum up, even if technical reasoning might be central for cumulative technological culture, theory of mind could have played a boosting role in the evolution, allowing humans to transmit information more widely without being constrained by the concreteness of the situation – schools are a good illustration of this. In this new story, tool-use skills are not stopped at the frontier of cumulative technological culture but considered as the *cause* of it – pedagogical skills becoming rather a *condition* for the modulation of the phenomenon.

The opacity

One consequence of cumulative technological culture is that there is now, in some cases, an important distance between the maker and the user, the former crafting tools whose use may be simplified, but the functioning opaque to the latter⁸ (Osiurak & Heinke, 2018; **Box 2**). This is particularly true for any tool involving an interface such as **cognitive tools** (e.g., smartphones) or other kinds of artifacts such as washing machines or TV monitors. However, this can also concern some artifacts without interface (e.g., a magnetic card to open a door). In this case, the user needs to learn the arbitrary relationship – sometimes based on symbols – between an action (e.g., pressing a

key/switch) and an expected effect (a letter on the screen). Interestingly, even the maker, who knows the functioning of the tool, has to learn this relationship, thereby becoming a user during the use. It is likely that the use of these “arbitrary tools” does not need mental making (i.e., technical reasoning), but rather low-level cognitive skills such as procedural memory or associative learning. Although this possibility remains to be tested empirically, evidence supports this. For instance, patients with Parkinson’s disease, known to impair procedural memory, meet difficulties with activities based on sequence learning, but not to use or select appropriately tools such as a knife or a hammer (Osiurak, 2014). The opposite pattern is observed in left brain-damaged patients. Some non-tool-using species can also use very easily touchscreens (Claidière et al., 2014), as do very young children despite limited skills to make new physical tools (Beck, Apperly, Chappell, & Guthrie, & Cutting, 2011; Chappell, Cutting, Apperly, & Beck, 2013). The idea that the use of these opaque tools needs low-level cognitive skills may sound as a variant of the manipulation-knowledge hypothesis. However, it must not. The manipulation-knowledge hypothesis describes how humans use any type of tools. By contrast, we propose that procedural memory/associative learning is involved only in the use of these opaque tools but not in the making and use of all the other categories of tools including those of early hominins and humans.

< Insert **Box 2** about here >

The call

Rewriting the story of tool use in cognitive sciences needs a radical epistemological shift. As explained, this shift might correspond to escape from the “*humans-are-manipulators*” view and to adopt the “*humans-are-makers*” view, offering a good starting point to inaugurate a new field labeled *Technition*. This field would aim at

gathering all research interesting in the neurocognitive bases of our ability to solve physical problems and to significantly transform our physical environment. As explained here, the study of technical-reasoning skills might be central in this field, which can be organized around key issues not only within the field itself but also at the crossroad of other fields of cognitive sciences (**Figure 3**). The last section presents some of these key issues.

< Insert **Figure 3** about here >

The issues

Motivation. It is sometimes stressed that early hominin and human tool use could have been developed by necessity to face environmental pressures (e.g., survival; Boesch & Tomasello, 1998; Wynn, 1993). This hypothesis has also been offered for nonhuman animals, but has received no empirical support (Koops, Visalberghi, & van Schaik, 2014; Sanz & Morgan, 2013). The question is why we keep on making tools that have no apparent interest in survival (e.g., TV remote). Instead of focusing on external incentives, a more Lorenzian view is to consider that we use tools because our technical-reasoning skills lead us to generate our own physical problems in an instinctive way (Osiurak et al., 2010). This could explain the presence of a human preference for using tools even when they are less effective than doing without them (Osiurak, Morgado, Vallet, Drot, & Palluel-Germain, 2014; Virgo, Pillon, Navarro, Reynaud, & Osiurak, 2017), a bias that has not been found in nonhuman tool-using species (e.g., New-Caledonian crows; Danel, Osiurak, & von Bayern, 2017).

Tool incorporation. Evidence has shown that tools can be incorporated in body representation (Cardinali et al., 2009; Maravita, Husain, Clarke, & Driver, 2001). This phenomenon occurs not only in humans but also in non-tool-using species trained to use

tools (e.g., macaques; Iriki, Tanaka, & Iwamura, 1996; for review, see Maravita & Iriki, 2004). It has been observed with simple tools, which increase the preexisting capacity of the user's biomechanical system (e.g., a stick that increases preexisting reaching capacities). However, humans can also use complex tools, namely, tools for which the user has no "natural" biomechanical predisposition (Osiurak, Rossetti, & Badets, 2017). For instance, we do not possess the natural capacity of cutting. At best, we can break bread with the hands, but this action is qualitatively distinct from that of cutting it. So, when we use a knife, the mechanical action offered by the use of this knife is qualitatively distinct from what the hand can do naturally. In this context, the issue is whether tool incorporation also concerns complex tools. The answer may be no, because complex tool use may require more than the preexisting motor-control system but also technical reasoning. Therefore, complex tool incorporation should occur neither in humans nor in nonhumans. This exciting issue remains open, notably if we use, one day, exoskeletons consisting of complex tool-like prostheses.

Construction. As repeatedly stressed above, technical reasoning may be critical not only to use tools, but also to make them or building construction. This prediction can open new avenues in many disciplines of cognitive sciences where the neurocognitive bases of tool making or construction are very rarely investigated. For instance, neuropsychologists interested in visuo-constructive skills generally assess whether patients can reproduce a pattern visually (focus on *visuo-*), but not whether they can perform appropriate mechanical actions to connect several pieces together to build something (focus on *-constructive*). There is also no study examining construction skills in left brain-damaged patients with tool-use disorders.

Secondary tool use. The ability to use one tool to create another (i.e., **secondary tool use**) is very specific to human species (Beck, 1980), although there are now four or

five observations of this behavior in nonhuman primates (e.g., Mannu & Ottoni, 2009). Nevertheless, this behavior remains rare in the wild (Shumaker et al., 2011). Early stone tools were already an instance of this behavior (i.e., the use of a hammer stone to create a flake useful to cut meat). Some cognitive archaeologists have explained this perhaps uniquely human trait by a specific enhancement of working memory capacity in early hominins and humans, allowing them to develop more and more complex sequence of tool-making actions (Haidle, 2010; Wynn & Coolidge, 2007). The introduction of the missing character – i.e., technical reasoning – might lead us to revise this assumption, by considering that working memory is not the *cause* of this trait but rather the *condition* for allowing the user to maintain a greater number of mechanical actions generated via technical reasoning. Said differently, it is far more likely that we will observe secondary tool use within a species if this species possesses the ability to generate spontaneously technical solutions to solve a problem. Future research is needed to explore this alternative, which emphasizes the central role of technical-reasoning skills.

Tool saving. The ability to **save tools** for future use is also characteristic to human species. It has been reported that some nonhuman animals such as apes (Mulcahy & Call, 2006) or ravens (Kabadayi & Osvath, 2017) might also show this behavior in an experimental context. Nevertheless, there is no observation of such behavior in wild animals. Tool saving is cognitively demanding because it imposes to plan an action (i.e., save a tool aside) for a potential future need, and not for a current one. In this way, tool saving is at the crossroad of tool use and what is called **future planning** (for discussion about future planning/foresight/future thinking, see Suddendorf & Busby, 2003; Suddendorf & Corballis, 2007). Surprisingly, tool saving – and more generally item saving – has received little attention, despite our propensity to continuously order and reorder our environment in order to facilitate the future search and retrieval of tools

stored. Research is clearly required here to investigate this ability, which is certainly not supported by specific tool-use skills, even if tool use can be an interesting way of investigating it.

Cumulative technological culture. Beyond the potential involvement of technical reasoning in this phenomenon, other important issues can be tackled here. For instance, unresolved issues concern the role of learners' versus teachers' cognitive skills as well as the individuals' characteristics, who are preferentially copied within a group (Kendal et al., 2018; Laland, 2004; Muthukrishna, Morgan, & Henrich, 2016; e.g., the best engineer with high technical-reasoning skills; the best pedagogue, with high theory-of-mind skills; the best friend, with a high degree of prosocialness; see Osiurak et al., in revision).

The end

To conclude, we would like to forestall potential skepticism, which could be to argue that there is no need to rewrite the story of tool use and, as a result, to promote a new field labeled Technition. We are convinced that many scientists do not require it to organize their thinking and the literature around the question of how humans transform the physical world. For them, this field already exists, at least in their head. Nevertheless, for many others, the contemporary collective organization of cognitive sciences leads them to consider that technical skills are peripheral to the debate about human cognition or based on low-level cognitive processes such as motor programs. This epistemological bias is not unique to cognitive sciences and can be found in other disciplines such as archaeology.

"The human mind is not a single cognitive phenomenon. It consists of many interconnected networks, each of which has its own evolutionary history. One such system that has been underappreciated in evolutionary studies, but which governs many activities in the modern

world, is skilled technical cognition. Unfortunately, this kind of thinking is not held in high regard in academic discourse where verbal and mathematical thinking are the primary tools of scholarship. And yet, for most of human evolution, day-to-day technical thinking was almost certainly more important to the evolutionary success of our ancestors. Even archaeologists, for whom technical remains are the primary data source, have tended to privilege language and symbol use in discussion of the modern mind..." Wynn et al. (2017, pp. 21)

"The following essay is based on the premise that much technical creativity occurs during the process of technical activity itself, such that new arrangements or possibilities emerge from the interaction of artisan, tools and materials. What cognitive abilities underpin such creative developments? In order to answer this question, it is necessary to start with a model of technical cognition. Unfortunately, a single comprehensive model of technical cognition has yet to be developed." Wynn and Coolidge (2014, pp. 45)

In this regard, the emergence of Technition might help scientists – not only cognitive scientists but also archaeologists, anthropologists or evolutionary biologists – to change their viewpoint by accepting that humans are also – if not first and foremost – a technical species. This epistemological shift is much more than simply introducing a new character, namely technical reasoning. As explained above, it can lead us to revise our way of addressing many questions, such as the role of theory-of-mind skills in cumulative technological culture, the link between tool-use and constructive disorders in brain-damaged patients, the role of working memory in secondary tool use or the cognitive bases of opaque versus physical tools. In sum, if such an epistemological shift occurs along with the development of a comprehensive, neurocognitive model of Technition, it will be easier to achieve even more dramatic advances about the origins of our unique technical mind.

Endnotes

¹ For instance, in the *Oxford Handbook of Cognitive Psychology* (1884 pages, 13 topics, 65 chapters), the term “tool” is employed only in 65 pages and only 13 times with the meaning of “physical tool” (only 1 occurrence for “tool use” and most occurrences concern the concept of statistical tool). There is neither topic, nor chapter on this aspect. The subtitle “Cinderella” here refers to an *American Psychologist’s* article written by David Rosenbaum, who drew a similar conclusion regarding the lack of interest in motor control from psychologists (Rosenbaum, 2005).

² Studies have reported that nonhuman animals such as great apes (Hanus, Mendes, Tennie, & Call, 2011; Mendes, Hanus, & Call, 2007) or corvids (Jelbert, Taylor, Cheke, Clayton, & Gray, 2014) can use water to obtain an out of reach reward. However, there is no evidence of such behavior in the wild, as reported in the comprehensive review on animal tool behavior by Shumaker et al. (2011).

³ Recent findings have challenged the “automatic motor-program activation” interpretation of the orientation effect reported in this paradigm in favor of the more parsimonious location coding account (e.g., see Pellicano et al., 2019; for a review, see Osiurak & Badets, 2016).

⁴ Technical reasoning is a specific kind of reasoning that is directed toward the physical world. In this respect, it must not be confounded with other forms of non-verbal reasoning, such as fluid cognition. More specifically, fluid cognition allows humans to develop logical thinking that does not need a precise understanding of physical constraints (e.g., Raven’s progressive matrices test). Evidence has shown dissociations between fluid cognition and technical-reasoning skills both at a behavioral level (e.g., De Oliveira et al., 2019) and at a neural level (prefrontal cortex/fluid cognition [see Blair, 2006] versus left inferior parietal lobe/technical reasoning [see below]). In addition, technical reasoning is not restricted to the spatial dimension of the physical world. To master the mechanical action “percussion”, for instance, requires much more than simply matching two objects – or more – spatially. It also needs to understand other properties (e.g., rigidity, weight) that go beyond the mere spatial dimension. The assumption that technical reasoning is not a form of spatial reasoning is also supported by the neuropsychological literature that has demonstrated that apraxia is a disorder that concerns mainly the left parietal lobe, whereas visuo-spatial deficits occur far more severely after damage to the right parietal lobe.

⁵ The role of exploration in the developmental trajectory of tool manipulation skills has been intensively investigated in works inspired by the Gibsonian approach to affordance. Although the concept of affordance has been a great source of inspiration, we opted not to use this term here because it can be employed with a multitude of meanings in the literature, sometimes meaning everything and its opposite (for a review, see Osiurak et al., 2017).

⁶ We are not saying here that the development of object-object manipulation skills has no impact on the causal understanding of the physical world. Of course, the more an infant or a child develop these skills, the more she or he is likely to explore her or his physical world and increase her or his technical-reasoning skills (and vice versa; for discussion about this aspect, see Legare, 2014). Nevertheless, we posit that this corresponds to independent forms of cognitive processes, each concerned by a specific goal (i.e., economy of motor actions/motor-control system versus understanding of physical principles/technical reasoning).

⁷ Because the observer and the model possess the same biomechanical constraints, the motor actions selected by both the observer and the model can be very similar, creating the illusion that the transmission has occurred at the motor level.

⁸ As a matter of fact, even if a professional knife maker intends to make a knife, it is very likely that she or he may use some materials that are not “natural” but already transformed (e.g., steel). In other words, even the concept of tool making is relative because many of us can make tools but only up to a point.

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Competing interests

The authors declare no competing financial interests.

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Table 1. Glossary

Apraxia of tool use	Inability to select and use appropriately familiar tools after brain damage.
Cognitive tool	Any external object that maintains, displays, or operates upon information in order to serve a representational function.
Complex tool use	Use of a tool to implement transformations that convert movements of the hands into qualitatively different mechanical actions (e.g., a knife to cut).
Construction	Two or more objects physically linked to produce a functional semi-permanent thing that is not manipulated in its entirety once produced.
Cumulative technological culture	Accumulation of socially learned information over generations, allowing humans to develop tools and technologies that are too complex to have been invented by a single individual.
Future planning	Ability to anticipate future needs, independent of current needs and over a relatively long timescale.
Imitation	Ability to copy a technical solution with fidelity.
Innovation	Emergence of a new technical solution, or use of an old technical solution, to solve new problems.
Manipulation knowledge	Knowledge about how to manipulate a familiar tool (also called tool-use motor program).
Mechanical knowledge	Non-declarative knowledge about physical principles, which is acquired through experience.
Micro-society paradigm	Paradigms modeling cumulative technological culture in experimental conditions where participants can share information either via direct (i.e., observation, communication or indirect transmission (i.e., reverse engineering). For instance, in vertical transmission chain paradigms, in each generation one member of the group is replaced with a new participant.
Motor-control system	System in charge of selecting and planning the most economical motor actions whatever the context (e.g., tool use, object transport).
Opacity/ Transparency	Amount of information that an individual can extract from looking at an artifact. The artifact is transparent if it provides enough information about how it is built (e.g., a simple spear), and opaque if not (e.g., a spear with a split-based bone point).
Prospective diagnosis	Ability to test for functionally relevant properties of an object before using it in a context of tool use, tool making or construction.
Secondary tool use	Use of one tool to make another.
Simple tool use	Use of a tool to implement motor-to-mechanical transformations that increase the user's sensorimotor capacities (e.g., a stick to extend reach).
Technical reasoning	Ability to solve physical problems on the basis of abstract physical principles acquired through experience. This reasoning is both analogical and causal.

Technition

Theory of mind	Ability to impute mental states to oneself and to others.
Tool making	Physical modification of an object so that it serves, or serves more effectively, as a tool.
Tool saving	Ability to save tools aside for future use.
Tool use	Use of any handheld physical implement that is used to make changes in the environment.
Transfer	Ability to transfer a technical solution learnt in a given situation to another one.

Box 1: Epistemological consideration

Like language, tool use is a hallmark of our species, even if we share the general ability with other species. It is largely acknowledged that the potential analogy between human and nonhuman language skills is flawed in that only humans might possess symbolic language skills. The analogy is also imperfect for tool use if we do not ignore our specificities (e.g., complex tool use, use of natural forces, secondary tool use). Nevertheless, for scientists, human tool use remains based on low-level cognitive skills – i.e., motor programs – as if we would consider human language to be only a matter of bucco-oral motor programs. Why do scientists have difficulties to see the intelligence – or *Intelligence* (Osiurak & Heinke, 2018) – hidden behind tools? A potential reason is that scientists order and categorize their objects of study based on major meta-theories. One of these is the classical procedural-versus-declarative-memory dichotomy (Anderson, 1983) that mirrors the popular distinction between manual and intellectual work. Given that it is difficult to explain explicitly what we understand when using tools, the natural answer is to tick the “procedural box”. This answer seems relatively intuitive. For instance, for more than a century, neuropsychologists have assumed that tool-use disorders belong to motor/gestural disorders (i.e., apraxia; Buxbaum & Kalénine, 2010; Buxbaum et al., 2015; Daprati & Sirigu, 2006; Heilman et al., 1982; Liepmann, 1908; Poizner et al., 2015; van Elk et al., 2014). Likewise, recent embodied cognition theories posit that tool use needs the simulation of past motor experience (Barsalou, 2008; Barsalou, Simmons, Barbey, & Wilson, 2003). Conversely, IQ tests have never included items requiring tool-use skills or understanding of physical principles (e.g., psycho-technical tests). To overcome this epistemological belief and start investigating the cognitive/intellectual aspects underlying tool use, it is perhaps useful

to assume that some types of knowledge can be non-declarative without being necessary motoric/procedural. After all, we know that very young children can start to develop a general, although incomplete, understanding of the principles of gravity or support (Baillargeon & Hanko-Summers, 1990). Yet, even adults show strong difficulties to explain them explicitly as well as many other mechanical principles they nevertheless apply frequently in everyday life (e.g., cutting, hammering, lever). Similarly, humans did not have to wait for Newton's discovery of the law of gravity to apply it in everyday life. But, Newton explained it explicitly, based on declarative knowledge. In sum, the development of a new field of cognitive sciences can emerge only if we go beyond the classical procedural-versus-declarative-memory dichotomy, opening the possibility to study our understanding of the physical world allowing us to master techniques – hence *Techn-ition* instead of *Cogn-ition*.

Box 2: Cognitive tools

One of the main consequences of the development of opaque tools, and particularly cognitive tools, is that they may modify our cognition. An interesting issue is whether cognitive tools progressively erase cognitive inter-individual differences. Recent evidence indicates that this is not the case in that people with the highest calculation/geographical skills remain the best when using a calculator or a map (Osiurak, Navarro, Reynaud, & Thomas, 2018). Another key issue is whether cognitive tools have a positive/negative effect on our neurocognition (Ophir, Nass, & Wagner, 2009; Sparrow, Liu, & Wegner, 2011; Storm & Stone, 2015). It has been shown that people can use them efficiently as an external memory (Sparrow et al., 2011; Storm & Stone, 2014). However, whether their massive use will lead to a progressive increase/decrease of attentional, calculation or memory skills is an outstanding yet fundamental issue (Ophir et al., 2009).

Figure Legends

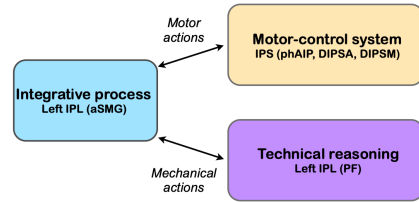
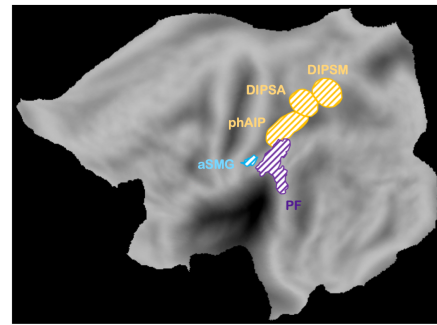
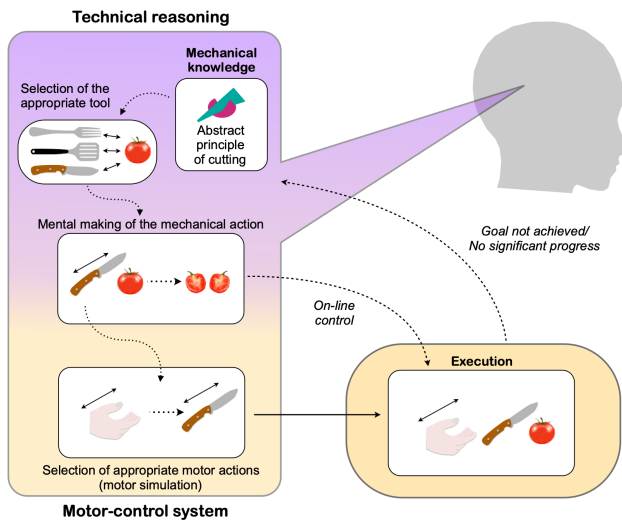
Figure 1. The technical-reasoning hypothesis. The left panel (cognitive view) illustrates the dynamics of technical reasoning (in purple) and how it interacts with the motor-control system (in orange) in a context of familiar tool use. However, the same rationale can be applied to any other technical activities, such as tool making or construction. The right panel illustrates the neurocognitive view of the technical-reasoning hypothesis. Technical reasoning involves the left inferior parietal lobe (IPL; particularly the area PF), whereas the motor-control system is notably supported by more superior parietal structures such as the intraparietal sulcus (IPS; phAIP: putative human anterior IPS; DIPSA: Anterior dorsal intraparietal sulcus; DIPSM: Medial dorsal intraparietal sulcus). The anterior portion of the left supramarginal gyrus (aSMG; in blue) could play a key integrative role between technical reasoning and the motor-control system.

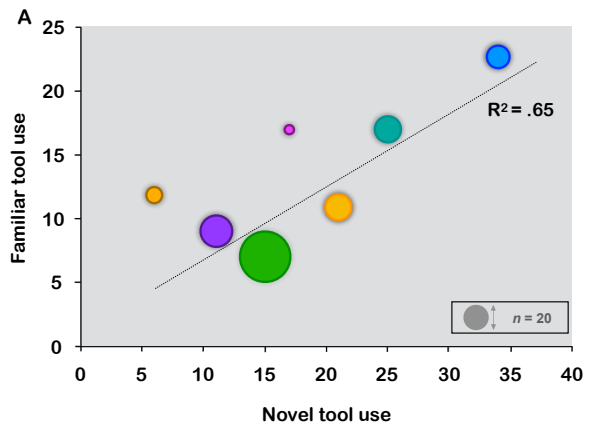
Figure 2. Evidence for the technical-reasoning hypothesis. (A) The figure depicts the strong link between familiar tool use and novel tool use in left brain-damaged patients, confirming that a same cognitive process (i.e., technical reasoning) is at work whatever the familiarity of the task. Each point refers to a study where both left brain-damaged patients and healthy controls were assessed on both tasks. Patients' deficit is expressed in terms of percentage of impairment as compared to healthy controls ($M_{Controls} - M_{Patients}$). (B) Lesion sites reported in voxel-based lesion-symptom mapping studies investigating familiar tool use and novel tool use in left brain-damaged patients. The area PF within the left inferior parietal lobe is the only brain area commonly found between all the studies. (C) Key finding of a recent neuroimaging meta-analysis on tool use (Reynaud et al., 2016). The analysis included studies where healthy participants had to focus on the appropriateness of the mechanical action (tool-object relationship). Results revealed activation of the left area PF (in red in the zoomed picture), suggesting that this area is deeply involved in understanding mechanical actions (i.e., technical reasoning). (D) Key finding from a recent neuroimaging meta-analysis on tool-use observation (Reynaud et al., revision). The results concern the contrast of studies where healthy participants had to observe tool-use actions minus non-tool-use actions. Again, a preferential activation of the left area PF is found (in yellow in the zoomed picture), indicating that people

reason technically not only to conceive mechanical actions with tools (aforementioned results) but also when watching others use tools.

Figure 3. Technition: A new field of cognitive sciences. Technition is represented here as a distinct field of cognitive sciences as working memory, future planning, and theory of mind. The key process is technical reasoning and its potential neural substrate might be the area PF within the left inferior parietal lobe. The key hypothesis is that technical reasoning is critical not only to use many kinds of tools, but also to make them or build constructions. Interestingly, in concert with other cognitive processes, technical reasoning could have allowed humans to develop unique abilities, such as using one tool to create another (secondary tool use; working memory), saving tools aside for future uses (tool saving; future planning) or improving tools over generations (cumulative technological culture; theory of mind). All these manifestations have led humans to make and use new tools such as cognitive tools, raising the issue as to whether their emergence could not change our neurocognition in the future. Key issues can be addressed within this field, such as for instance whether we can incorporate, strictly speaking, any kind of tools (body) or what incites us to constantly transform our physical environment with tools (motivation).

Cognitive view
Neurocognitive view





- Goldberg & Hagmann (1998)
- Osieurak et al. (2009)
- Heilman et al. (1997)
- Goldberg et al. (2007)
- Jarry et al. (2013)
- Hartmann et al. (2005)
- Bartolo et al. (2007)

