Looking for Intoolligence: A Unified Framework for the Cognitive Study of Human Tool Use and Technology

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DOI:
10.1037/amp0000162

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Abstract

Humans have considerably modified their environment, by making and building a considerable amount of tools, technologies, and constructions. This unique ability compared to other animals is the focus of researchers in different fields of psychology. However, there is confusion about the definitions proposed, generating difficulties to make connections between those different fields. This article presents the first unified framework (i.e., *Intoolligence*) aiming to overcome these issues by focusing on the cognitive processes involved in the different forms taken by human tool use and technology, rather than on the overt behavior. To lay the foundation for *Intoolligence*, we first address a series of epistemological misconceptions, which are the root cause for the current confusion. Particularly, we discuss the limitations of the widespread idea that tool use relies on specific cognitive skills, centered on the manipulative aspect of tool use. Based on this analysis, we develop details our framework, which is based on the key principle that making and using are two independent cognitive steps. This distinction allows us to redefine tool use by breaking it down into three modes: Assistive tool use, arbitrary tool use, and free tool use. This article opens a new chapter in the topic of human tool use and technology.

Keywords: Tool Use; Tool Making; Construction Behavior; Technical Reasoning

Introduction

We are researchers in cognitive sciences, interested in the neurocognitive bases of tool use. Like many of our colleagues, our work is deeply inspired by neuropsychological models. This theoretical choice, although deliberate, is not neutral. Neuropsychological models focus on how patients are able to use physical, manipulable tools such as a hammer or a toothbrush. However, they do not aim to account for difficulties with the use of many objects or technologies that can also be viewed as tools, such as computers, TV sets or cars. Epistemologically, the problem is that the reason of why this is not the case has never been addressed, generating confusion when the time comes to interact with colleagues from other fields. Thus, there is hardly a week that passes without colleagues or students asking us whether the neuropsychological model we are presenting is appropriate for the study of driving, for instance. The next question inevitably is: "According to you, is a car a tool?" Likewise, it sometimes happens that engineers or researchers contact us to help them to think about the usage of new technologies, such as touch screens. However, after a few meetings, we realize that the neuropsychological models based on the use of physical, manipulable tools are not very useful for modeling the use of these technologies. Perhaps this time could be greatly saved – and more fruitful collaborations could have been developed – if we had understood that the term tool is not a sufficient reason to link distant fields of research. For a long time, these uncomfortable situations have made us believe that we must better clarify what we mean by tool and, as a result, our research question. Now, we understand that this project is pointless in terms of scientific progress, because this would not lead to improve communication between researchers interested in the topic. Instead, what is needed is a unified framework that aims to give an overview of the cognitive processes involved in the different forms taken by human tool use and technology. This is all the more true for students, who need to frame their work, by knowing where their research begins and where it ends.

The goal of this article is precisely to provide such a framework, with the ultimate goal being to facilitate the theoretical interactions between scientists, and between scientists and students working in different fields of psychology on "tool use" – neuropsychology, comparative psychology, developmental psychology, experimental psychology, applied psychology, ergonomics, or human-computer interaction. This framework is called *Intoolligence* to refer to the intelligence involved in tool use and making, but also more generally, in behavior oriented toward the modification of the environment in an adaptive way, such as construction behavior. Humans do not only use knives, hammers or pencils, they also build roads, houses, and bridges. So, the challenge is to propose a unified framework encompassing all these different modes of interaction. The aim of *Intoolligence* is to rise to this challenge. *Intoolligence*'s main message is that the cognitive processes involved are multiple and depend on the mode of interaction (construction, assistive tool use, etc.). To understand these modes, we will begin by presenting a series of epistemological obstacles (i.e., false beliefs) that we will try to surmount. Based on what we learn once we overcome these obstacles, we shall propose the key principle that making and using are two independent cognitive steps that need to be understood separately. This will allow us to redefine tool use by breaking it down into three modes: Assistive tool use, arbitrary tool use, and free tool use. Finally, we will discuss how this framework can be useful for opening new avenues for future research.

False beliefs

False belief 1: Any definition of tool use is cognitively neutral

As every scientist knows, a topic cannot be adequately addressed without defining first. So, it may sound provocative to claim that there is no point in defining what a tool is. Yet, the process of defining something is not neutral: To define is to set limits. In this section, we argue that current cognitive models of tool use are biased by our way of defining tools, leading us to consider that tool use could be based on specific cognitive processes, distinct from those involved in construction.

The most comprehensive attempt to characterize the different forms of tool behavior is that of Beck (1980; Shumaker, Walkup, & Beck, 2011; see **Table 1**). His definition was developed in the field of animal psychology, but has been widely accepted in other fields, such as experimental psychology (e.g., Wagman & Carello, 2003) or neuropsychology (e.g., Farnè, Iriki, & Làdavas, 2005). This definition places heavy emphasis on manipulation, which is a key criterion to distinguish tool use from tool making or construction. The risk, however, is to misinterpret this definition by believing that: (1) Manipulation-centered cognitive processes must be central to any models of tool use, and (2) Tool use is based on specific cognitive skills. Let us address these two aspects in turn.

< Insert Table 1 about here >

It is common in neuropsychology to employ the term tool to refer to any handheld physical implement that is used to increase sensorimotor abilities. In a way, this conception of tool use is in line with Beck's definition, by focusing on the criterion of manipulation. What is surprising – or may be not – is that most neuropsychological models of tool use assume that humans store specific motor programs or sensorimotor knowledge containing information about how to manipulate tools (Cubelli, Marchetti, Boscolo, & Della Sala, 2000; Heilman et al., 1982; Rothi, Ochipa, & Heilman, 1991; van Elk, van Schie, & Bekkering, 2014). This is the chicken and the egg question: Has this definition framed the models developed or vice versa? Perhaps both simply reflect the profound belief that tool use is only a matter of manipulation, and does not require any intellectual or reasoning skills. In this context, it becomes inevitably that everyone agrees with the definition and the models developed, because the models are precisely the most likely answers offered to the problem delimited by the definition.

An alternative scenario could be to consider that manipulation is not critical to define tool use, notably because it is not always so easy to identify the motor action associated (Goldenberg, 2013). For instance, while preparing this article, we are in an office. If we take a quick look around, we can see paper clips, sheets of paper, a photograph, a small box, a ruler, elastic bands, a scotch tape, a keyboard, and so on. Most of these tools have no clearly defined manipulation and are not really manipulated during use in the first place. So, are these objects tools? This kind of question is never really addressed in the neuropsychological literature. Perhaps, the examples proposed in articles or the items employed in tasks consist of tools for which motor actions are implicitly easily recognizable. The corollary is that these tools are not chosen randomly and, as a result, are far from representative of the tools used in everyday life (Osiurak, Jarry, & Le Gall, 2011). So, at this point, there are at least two possible choices: Either we keep on ignoring those tools with no clear motor action associated (e.g., what is the motor action for a sheet of paper?) and continue to formulate theories based on a small proportion of tools with characteristic movements (e.g., perhaps we can consider that a hammer requires broad elbow movements), or we acknowledge that the current theories of tool use are too restrictive and unsatisfactory to grasp the cognitive processes underlying how humans interact with all types of tools. Our choice is the latter.

Another potential misuse of any definition of tool use is to view it as bijective, namely: Tool behavior is exclusively associated to specific cognitive processes, and vice versa. Said differently, this bijection implies that the cognitive process enabling a species to use tools are the same in another tool using species. In addition, the corollary of this bijective belief is that non-tool behavior, such as construction, involves cognitive processes distinct from tool use, which are also shared by all the species showing this behavior (i.e., tool use ↔ *cognitive processes A* versus construction ↔ *cognitive processes B*, irrespective of the species in question). In fact, Beck (1980) himself stressed that it is a mistake to view any definition of tool use as one of cognitive distinctness rather than of convenience. He also warned about mistakenly seeing tool use as cognitively distinct from construction behavior. Put simply, he suggested considering construction separately from tool behavior because nothing is held or carried during or just before the use. For him, tool use is not based on higher-level cognitive skills, and construction on lower-level cognitive skills, or vice versa. Rather, both can be based on different cognitive levels. In line with this, evidence has indicated that both tool use and construction behavior can be based on either flexible or more rigid, preprogrammed cognitive skills (Hansell & Ruxton, 2008).

As a matter of fact, there is also no bijection in humans: Tool behavior has no cognitive specificity, and we have certainly as much to learn at a cognitive level from construction behavior as we do from tool behavior. This aspect can also be illustrated by the following example, which shows the confusion that can arise when attempting to identify an observation as an instance of tool use. Imagine someone who realizes that her roof is leaking. If she grasps a glass and holds it to collect water, this is an instance of tool use. However, if she puts it on the floor, so that it collects the water, and goes away, this may be considered as an instance of construction behavior. If she cuts a plastic bottle in half and collects the water with it, this is an instance of tool making, but if she puts the bottle on the floor, this becomes a clear instance of construction behavior. Regardless of the course of action she decides to take, this example demonstrates that the label given to the behavioral pattern is not really important. What does matter are the cognitive processes that led this individual to solve the physical problem of water leaking through the roof. In broad terms, the same cognitive processes can be at work, irrespective of how the behavior is labeled (tool use, tool making or construction).

To sum up, any definition of tool use is only of convenience, and must not be taken as a theoretical starting point to build models. We use physical tools, but we also use a wide variety of cognitive tools (e.g., calculators, diaries) or more voluminous artifacts that are not always considered as tools (e.g., washing machines, cars). We make tools too. And, we are compulsive builders as evidenced by the way we had to modify our physical environment. As a result, the perhaps foremost issue is to understand what are the cognitive processes involved in the different interactions we have with our physical environment, irrespective of whether the observation can be labeled as tool use, tool making or construction behavior. This is the project of *Intoolligence*. This project diverges from current cognitive models of tool use (e.g., van Elk et al., 2014), for which the focus is mainly on tool use, thereby ignoring construction behavior in humans. As discussed, these models have the limitation of exaggerating the role of manipulation in tool use simply because the underlying core assumption is that tool use has to be understood independently from other behavioral patterns, such as construction.

False belief 2: Modern humans are tool users, not tool makers

We have argued that tool use has no cognitive specificity in that the same cognitive processes can be involved in both tool use and construction behavior (i.e., absence of bijection). Here, we go further and claim that tool use, construction behavior and also tool making can be, in some cases, based on the same cognitive processes. In addition, *Intoolligence* proposes that the selection of an object/tool – irrespective of whether it is already made or not – is also an instance of making or, more specifically, of mental making. In this section, we discuss evidence in favor of this.

Humans are unique in constantly improving their tools over generations, a phenomenon called cumulative technological culture (Boyd & Richerson, 1985; Tomasello, Kruger, & Ratner, 1993). The major consequence of this phenomenon is that we use tools that have been made by others (e.g., a knife bought from a supermarket). This is a problem for psychologists because this can create the illusion that humans – and particularly modern humans – do not make but only use tools[1]. This is true for a certain category of tools (i.e., arbitrary tool use, e.g., light switches, see below). However, in many other cases, modern humans keep on making mentally the tools they use (see the aforementioned "roof-leaking" example), even if the current environment leads them more often to select the appropriate ones instead of physically making them. Simply, understanding this needs to escape from the behavioral conception of tool making.

Four behavioral patterns are only described as modes of making (Shumaker et al., 2011; p. 11)[2]: Detach, subtract, add/combine, and reshape. In this definition, the selection of an appropriate object/tool is not viewed as a mode of making. So, if we consider that tool making, tool selection and tool use are based on distinct cognitive processes, it could be hypothesized that they can be impaired independently. As a matter of fact, neuropsychological evidence supports the idea that these three types of behavior are based on common cognitive processes – at least for some physical tools, but not "arbitrary tools" (see below). More particularly, some left brain-damaged patients can encounter serious difficulties in using everyday tools such as a hammer or a spoon, a disorder called apraxia of tool use (De Renzi & Lucchelli, 1988; Goldenberg & Hagmann, 1998a; Goldenberg, Daumüller, & Hagmann, 2001; Heilman, 1973). They can, for instance, attempt to pound a nail with a fork or to rub the hammer on the nail. In other words, their difficulties suggest that they are unable to generate the appropriate mechanical actions. Interestingly, a series of studies have shown that these patients can also be impaired when asked to solve mechanical problems by using novel tools (e.g., extracting a target out from a box by levering; see **Figure 1**; Bartolo, Daumüller, Della Sala, & Goldenberg,

[1] A potential epistemological bias can consist in focusing on the recent tools that humans have made, and for which many, if not most, of us do not understand how they work (i.e. arbitrary tool use; e.g., computers, remote controls, washing machines and so on; see below). However, we have to keep in mind that our world has considerably changed on this aspect, particularly for the last two centuries. For a long time, humans have to systematically use physical tools requiring the understanding of the mechanical actions intended. The procedural memory hypothesis could be influenced by the current technological configuration, leading to think that all our interactions are only based on the ability to learn motor skills associated with tool use. As explained in this section and later, this can be true for some of the tools we use now, but not for the other part, which is certainly more representative of the tools used by our species over evolution.

[2] The term of making is used here instead of the term manufacture as proposed by Shumaker et al. (2011).

2007; Goldenberg & Hagmann, 1998b; Goldenberg, Hartmann-Schmid, Sürer, Daumüller, & Hermsdörfer, 2007; Goldenberg & Spatt, 2009; Hartmann, Goldenberg, Daumüller, & Hermsdörfer, 2005; Heilman, Maher, Greenwald, & Rothi, 1997; Jarry et al., 2013; Osiurak, Jarry, Lesourd, Baumard, & Le Gall, 2013a; Osiurak et al., 2009; for reviews, see Baumard, Osiurak, Lesourd, & Le Gall, 2014; Goldenberg, 2013). For instance, they can select a stick far too short or not rigid enough to reach the target. Their difficulties can also concern the inability to fold a wire to create a hook-like tool, which is a pure instance of tool making.

< Insert Figure 1 about here >

In sum, these findings suggest that specific reasoning skills – hereafter called technical reasoning (i.e., the ability to reason about physical object properties; see below) – are in charge of both the use/selection of everyday, familiar tools and the use/selection/making of novel tools. Converging evidence from neuroimaging and neuropsychology has indicated that these reasoning skills could involve the left inferior parietal cortex, and more particularly, the architectonic area PF (Parietal area *F*; see Caspers et al., 2006), located within the anterior portion of the supramarginal gyrus (Goldenberg & Hagmann, 1998b; Goldenberg & Spatt, 2009; Orban & Caruana, 2014; Osiurak et al., 2009; Peeters, Rizzolatti, & Orban, 2013; Reynaud, Lesourd, Navarro, & Osiurak, 2016). This brain area that does not exist in nonhuman primates might be the neurocognitive basis for the ability to mentally make tools. Before going on, we would like to stress again that these reasoning skills are not necessarily involved in all our interactions with tools in that some tools are not mentally made before use (i.e., arbitrary tool use; see below). In addition, we are not saying that someone who uses a "premade" tool is necessarily able to physically make it. Many if not most of us can use knives with steel blades without being able to work steel. Rather, *Intoolligence* assumes that the same reasoning is at work when someone physically makes a tool or when this individual mentally makes it before use. In this context, the inter-individual differences in terms of capacity of making depend on the amount of mechanical knowledge possessed by individuals.

False belief 3: Procedural memory supports all instances of tool use

Our way of thinking about human cognition is shaped by meta-theories, one of the most influential being the procedural versus declarative memory dichotomy (**Figure 2**; e.g., Anderson, 1983). Declarative memory is thought to mediate recollection of facts and events and rely on temporal lobe structures. By contrast, procedural memory mediates the production of new motor skills and habits, and involves a fronto-striatal network. Given the emphasis placed on manipulation and motor components in definitions of tool use, a theoretical rapprochement has been suggested between procedural memory and tool use in the literature (e.g., Roy, Park, Roy, & Almeida, 2015; van Elk et al., 2014; see also Hermsdörfer, 2014). This is also spontaneously proposed by students in psychology or neurosciences, again demonstrating the impact of meta-theories on our conception of human cognition. This rapprochement is true in some cases (i.e., arbitrary tool use, see below) but could be wrong in others. Let us begin with the former.

< Insert Figure 2 about here >

Procedural memory is known to be impaired in patients with Parkinson's disease because of damage to basal ganglia due to the disease. A significant body of literature has indicated that these patients encounter difficulties in driving. These difficulties do not concern the navigation, but rather the ability to perform the procedures useful for controlling the vehicle (e.g., gear change; see Uc et al., 2009, 2011). These patients are also impaired in learning sequences of movements (Benecke, Rothwell, Dick, Day, & Marsden, 1987), which are critical for some activities such as typewriting (Rieger, 2004; see also Goldenberg, 2013) or when the interaction is constrained by the use of an interface (e.g., smartphones, automated teller machines). Evidence also shows that procedural memory is a key process in the practice of musical instruments (Simmons, 2011). In broad terms, procedural memory could support the use of tools whose use needs the learning of an arbitrary relationship between a motor action and its effect, without that the user necessarily understands the underlying physical principles or has to select the tool useful for the given task (i.e., free tool use, see below).

The risk, however, is to believe that all tool use interactions is based on procedural memory. This is, for instance, the perspective taken by Roy and Park (2015; see also Roy and Park, 2010; Roy et al., 2015; for discussion, see Osiurak, in press), who developed a paradigm aiming to assess the procedural aspects of tool use. Their task consisted in learning how to use a stylus to perform a mirror-tracing task. As suggested by Roy and Park (2010), a stylus is a tool, there is no doubt about it. However, asking someone to learn how to use it in a mirror does not tell us anything about how she is able to understand how the stylus works and whether she will be able to select an appropriate tool in the future for tracing. Perhaps their task assesses procedural aspects, but the presence of a tool does not justify the idea that tool use in general is a matter of procedural memory. For instance, Claidière, Smith, Kirby and Fagot (2014) recently showed that social learning can occur in baboons, using a paradigm wherein baboons had to reproduce visual patterns on a tool, namely, a tactile computer screen. Yet, baboons do not use physical tools in the wild. It is very likely that they interacted with the computer screen without understanding how it worked, as it is the case for most people. So, the processes supporting tool use can be multiple and it would be unreasonable to associate them with specific cognitive skills.

Further evidence supports the view that all instances of tool use are not necessarily based on procedural memory. As discussed, the left inferior parietal cortex could be critical for the ability to select appropriate physical tools or to perform relevant mechanical actions. However, this brain area does not belong to the fronto-striatal network supporting procedural memory. In addition, patients with Parkinson's disease do not show these difficulties despite impaired procedural memory (Giovannetti et al., 2012). In broad terms, there is a clear double dissociation between, on a one hand, the ability to select and correctly use physical tools (technical reasoning; left inferior parietal cortex) and, on the other hand, the ability to use tools based on the learning of arbitrary relationships (procedural memory; fronto-striatal network).

This discussion leads us to question the validity of the procedural versus declarative memory dichotomy (**Figure 2**). It is very likely that this view contributes to perpetuate the folk belief that manual work does not require any reasoning or intellectual skills, as compared to intellectual work. More specifically, this dichotomy could bring us to think that the tool use skills are necessarily motoric, because of their implicit nature. However, even though we are not systematically able to *explain explicitly* the physical principles underlying our interactions with the world, we do *understand* most of them. Humans did not have to wait for Newton's discovery of the law of gravity to apply it in everyday life! Similarly, most people can select a knife with a sharpened edge to cut a tomato without being able to explain explicitly the cutting action. Infants as young as 4.5 months of age understand that objects cannot remain stable without support (Baillargeon, Needham, & Devos, 1992). Yet, they are unable to explain the principle of support, namely, an object resting on a support is stable only if a perpendicular line drawn through the object center of gravity falls within the support's boundaries. Even though most adults are also unaware of this principle, they use it systematically in everyday life.

In sum, *Intoolligence* posits that we possess reasoning skills based on implicit knowledge about how the world works. These skills share with procedural memory the "implicit" aspect, and with declarative memory the "reasoning" aspect, leading us to revise the classical procedural versus declarative dichotomy (**Figure 2**). They could be particularly involved in the selection and use of physical tools. Nevertheless, in some circumstances, when the interaction corresponds to an arbitrary relationship between a motor action and its effect, the key cognitive process could be procedural memory.

False belief 4: Tool use is a matter of manipulation

For more than a century, most neuropsychological models have assumed that tool use is based on the storage of manipulation knowledge, also called gesture engrams or visuo-kinesthetic engrams (Heilman et al., 1982; Rothi et al., 1991; van Elk et al., 2014; for a somewhat similar view, see also Xu, Humphreys, & Heinke, 2015; Xu, Humphreys, Mevorach, & Heinke, 2017; Yoon, Heinke, & Humphreys, 2002). The key assumption is that this knowledge offers economy by avoiding the reconstruction of the motor program *de novo*. For instance, this knowledge can provide the information that "a hammer is grasped at the handle and used with a back-and-forth swinging movement" (van Elk et al., 2014, p. 237). The manipulation knowledge hypothesis is also consistent with the current, widespread approach to embodied cognition, which assumes that knowledge is based on the simulation of our past sensorimotor experience (Barsalou, 2008; Borghi & Riggio, 2009; Glenberg, 1997; Yee, Chrysikou, Hoffman, & Thompson-Schill, 2013). Thus, given that tool use would be first and foremost a matter of manipulation, the simulation of motor experience would be critical for this activity. Evidence has challenged this hypothesis.

First, a significant body of literature from left brain-damaged patients has indicated a strong link between the ability to use everyday tools and to solve mechanical problems by using novel tools (see above; **Figure 1**). To solve mechanical problems requires reasoning about the physical properties of both tools and objects, that is, about allocentric relationships that do not imply the body itself (Osiurak & Badets, 2016). Yet, manipulation knowledge encodes egocentric relationships, that is, information about how the body interacts with tools. In other words, the manipulation knowledge hypothesis cannot account for the aforementioned link. Second, manipulation knowledge is supposed to be contained within the left inferior parietal cortex. This idea has been extrapolated by using tasks wherein patients have to judge whether the hand posture shown is correct to use physical tools (i.e., egocentric relationship). However, a recent, comprehensive neuroimaging meta-analysis revealed that performance in this kind of tasks is associated with activation of the intraparietal sulcus (putative human homolog of anterior intraparietal sulcus, phAIP; anterior dorsal intraparietal sulcus, DIPSA; medial dorsal intraparietal sulcus, DIPSM; Reynaud et al., 2016). Interestingly, this study reported that the left inferior parietal cortex is activated, but rather in tasks where people have to decide whether the mechanical actions between tools and objects are correct, irrespective of the familiarity of the stimuli presented (i.e., allocentric relationship). In other words, these findings are inconsistent with the idea that the left inferior parietal cortex stores manipulation knowledge. Rather, they seem to demonstrate that this brain area could be involved in the ability to reason about physical object properties, that is, technical reasoning.

At this point, a critical question is why the manipulation knowledge hypothesis is so widely accepted within the scientific community, while some authors have already argued that no manipulation knowledge is needed to explain how humans use most of physical tools (e.g., Goldenberg, 2013). Again, this hypothesis is consistent with the false belief that tool use does not require any intellectual skills. It is also very likely that the methodological choices contribute to this belief. For instance, one of the tasks the most commonly employed to assess apraxia of tool use is the pantomime task, i.e., demonstrating the use of a tool without holding it in hand (Bartolo, Cubelli, Della Sala, & Drei, 2003; De Renzi, Faglioni, & Sorgato, 1982; Goldenberg, Hartmann, & Schlott, 2003; Poizner et al., 1995; see Lesourd et al., 2013). Perhaps the design of this task encourages researchers and clinicians to interpret the difficulties as "gestural" and not as "tool-centered" because the deficit is expressed through the gesture examined in isolation. However, several studies have highlighted that this task is not a "passive" task, but a creative task relying a multitude of different cognitive processes involved in tool use per se (e.g., working memory, semantic memory, mechanical knowledge; Bartolo et al., 2003; Goldenberg, 2003; Goldenberg et al., 2003; Roy & Hall, 1992). In fact, the manipulation knowledge hypothesis could have been developed on the narrow question of how people interact with tools in everyday life, perhaps by focusing on experimental and clinical tasks where the only aspect assessed – or at least observed – is the gesture carried out by the subject. However, in everyday life we do not only "gesticulate" with tools, we use them to solve physical problems. **Figure 3** gives an example of this.

< Insert Figure 3 about here >

In sum, evidence is still needed to support the manipulation knowledge hypothesis. Rather, it appears that this hypothesis has been developed based on methodological and epistemological choices leading scientists to focus on the manipulative aspect, thereby ignoring the preparation step which frequently occurs when we use tools. A possibility could be to assume that manipulation knowledge supports arbitrary tool use. The corollary is that this mode of use should be impaired after damage to the left inferior parietal cortex. However, as discussed, a fronto-striatal network supporting procedural memory seems to be a better candidate for this mode of use.

The framework: *Intoolligence*

So far, we have stressed the epistemological obstacles that contribute to the confusion about the cognitive bases of human tool use and technology. Here, we present the unified framework *Intoolligence* that aims to surmount these obstacles by specifying the different cognitive processes involved in the different types of interactions we have with our physical world (**Table 2**). This framework is based on the distinction between the making[3] step and the use step. The next section focuses on explaining this key principle.

< Insert Table 2 about here >

[3] As discussed so far, *Intoolligence* posits that there is no theoretical reason to distinguish between tool making and construction at a cognitive level. So, the terms maker/making will be also used to refer to builder/building.

Putting distance between the maker and the user

Imagine a farmer living in a rainy country, who has to go to his henhouse everyday to collect eggs. Imagine he crafts an umbrella with wood and leaves and uses it to go to the henhouse. This is an instance of tool making/use because the farmer intends to use the umbrella as a tool. Imagine now that he is bored with having to hold the umbrella each time he has to collect eggs. So he decides to build a roof between his home and the henhouse. We can also consider that this is an instance of tool use, at least the first time he uses it, even if the roof is not held in hand. However, the question is whether the roof is still a tool after the second use and particularly after several days when he will forget that he built it. In this case, a temporal distance begins to appear between the making and the use. This distance can even be greater if someone else buys the house. And, what about if a cat uses it to take shelter? The fact that a certain distance can exist between the maker and the user – who can be the same individual or not – has already been stressed in the literature and has led to the distinction between tool use, tool making and construction (see Shumaker et al. 2011). The idea is that benefiting from a construction does not need to "understand" how it is built. In addition, the distance between the maker and the user can also concern different species, such as the aforementioned example of the cat and the roof, or a dog with a niche. These different examples illustrate the key principle of *Intoolligence*: Making and using are two independent cognitive steps that need to be understood separately. Someone can make a tool or a technology without using it, and vice versa. This principle is relatively trivial in that we spend time to use tools made by others – as well as to build construction or to make tools for others. Nevertheless, this has never been considered as critical to any framework for the study of human tool use or technology (see Reynolds, 1993).

Cognitive step 1: Mental making

The making step can be characterized as follows. First, this step aims to solve a physical problem in the environment. This can be to build a bridge to pass over a river, to craft a knife to improve the cutting of meat, to create a candle to light a house, or to build a shelter for safety. Second, the individual who stands to benefit (i.e., the user) is not necessarily the maker. Third, the making necessarily occurs before the use.

Instances of making: Physical making, construction, selection and fixing

Different situations can be labeled as making. The first is what we call physical making as defined by Shumaker et al. (2011). This can be to cut a branch from a tree so as to use it as a perch, or to assemble several pieces of wood and stone to create a knife. The second is construction behavior, such as building a house or using a plastic bottle to collect water. The third is the selection of an appropriate physical tool to complete a task. As discussed before, the selection of an appropriate knife among several utensils needs to reason about the physical properties of the object to be cut. However, no mental making is required when the interaction is *physically constrained*, such as in arbitrary tool use. We will discuss this point in more detail below. The fourth is fixing. When we detect that a tool/construction does not work as it should, we generally attempts to establish a diagnosis. The present framework assumes that technical reasoning skills (see below) are also involved in fixing. Note that fixing can occur during the use, by interrupting it. For instance, while pounding a nail, we can realize that the nail meets difficulties to be driven into the wall. In this case, we stop hammering, and reason about the technical reasons of these difficulties. One solution can be to reorient the nail. Another can be to change the nail or to think about another technical solution.

The key cognitive process: Technical reasoning skills

> Now that I am writing, it is essential that I conceive my paper as a surface for inscription. If I failed to do that, I should have to stop my work. But if I wished to light a fire, and no other materials were by, the essential way of conceiving the paper would be a combustible material. (James, 1890/2007, p. 333)

The key cognitive component of mental making is technical reasoning (Osiurak, 2014; Osiurak & Badets, 2016; Osiurak, Jarry, & Le Gall, 2010), a concept close to causal reasoning (Penn, Holyoak, Povinelli, 2008; Povinelli, 2000), mechanical reasoning (Hegarty, 2004), structural inference (Goldenberg & Hagmann, 1998b) or naïve/intuitive physics (McCloskey, 1983). This reasoning enables us to solve physical problems such as those enumerated above. It is based on mechanical knowledge that contains abstract information about physical principles (e.g., support) or mechanical actions (e.g., cutting). When we detect a physical problem, we start to reason by using mechanical knowledge, providing us with potential technical solutions. In this way, this reasoning is causal because it allows us to foresee the potential effects of the mechanical actions on the environment. It is also analogical because the abstract nature of mechanical knowledge offers the opportunity to transfer what we understood in one situation to another situation. Simply, as suggested by James (1890/2007; see also Duncker, 1945; Maier, 1930), when using this reasoning, we have to identify in the present situation – or from memory (see below) – the physical properties of tools and objects that can be exploited to perform the mechanical action intended. If someone intends to build a bridge to pass over a river, she can use the principle of "bridge": Something long enough to connect two points as well as solid enough to be a good support. This can be a wooden board, if the river is narrow and if its usage is reserved for a single individual. However, this will be a long steel slab if the river is larger and reserved for a car. Regardless of the materials employed, the same physical principle is applied. Evidence indicates that these reasoning skills might rely on the left inferior parietal cortex, and particularly the cytoarchitectonic area PF within the supramarginal gyrus (Reynaud et al., 2016) [4].

Getting tools and objects: Semantic memory

A significant body of evidence has indicated that semantic memory (temporal lobes, particularly the left) and real tool use can be impaired independently from each other (Bartolo et al., 2007; Bozeat, Lambon Ralph, Patterson, & Hodges, 2002; Buxbaum, Schwartz, & Carew, 1997; Forde & Humphreys, 2000; Goldenberg & Spatt, 2009; Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000; Lauro-Grotto, Piccini, & Shallice, 1997; Negri, Lunardelli, Reverberi, Gigli, & Rumiati, 2007; Osiurak et al., 2008, 2009; Silveri & Ciccarelli, 2009; for a review, see Osiurak, 2014; Osiurak & Badets, 2016). The corollary is that semantic memory is neither necessary nor sufficient, raising the issue of what is the role of this memory system for tool use. When we engage in tool use actions, all the tools and objects needed are not always directly available, so we need to go get them. *Intoolligence* posits that this ability is based on semantic memory because it requires an organized search within our memories based on semantic categories (Osiurak, 2014; Osiurak & Badets, 2016; Osiurak et al., 2008). Episodic memory is

[4] *Intoolligence* assumes that, to use tools, there is no need for additional manipulation knowledge. Nevertheless, an alternative interpretation is that the human brain is organized into several routes for action. In this view, when manipulation knowledge is impaired, other cognitive processes (e.g., technical reasoning) compensate for the deficits (e.g., see Buxbaum, in press; Caruana & Cuccio, in press; Rothi et al., 1991). This interpretation is nevertheless questionable due to epistemological and theoretical problems as discussed in detail elsewhere (Goldenberg, 2013; Osiurak, in press; Osiurak & Badets, 2016, in press).

needed to remember precisely what tools we have, and where they can be. However, semantic memory helps us to increase our search in episodic memory by using broad categories. Let us come back to the painting and the wall example. If someone intends to hang up the painting, nothing is present except the painting and the wall. Nevertheless, this individual can begin to use mechanical knowledge to reason about a mechanical action useful to solve this physical problem. The fact is that this does not need to have all the tools and objects present. He can reason about the appropriateness of nails and hammers he possess in the workshop. In this case, he needs episodic memory to remember the specific physical quality of these tools. Nevertheless, semantic memory is critical to help him to know where to search – within episodic memory and, as a result, in the real world –, such as perhaps in the tools he usually used to decorate her home or repair things. So, for *Intoolligence*, semantic memory is not involved in the reasoning about the mechanical actions, but in the organization of the search within memory.

We never stop acquiring mechanical knowledge

Evidence indicates that 3 and 4.5 month-old infants are able to realize that objects cannot remain stable without support (Needham & Baillargeon, 1991; see Baillargeon et al., 1992). Nevertheless, they are not surprised if only a small portion of the object is in contact with the support. This suggests that, until the age of about 6 months, children consider *any* amount of contact between the object and the support sufficient for the object to be supported. Beginning around 6.5 months of age, infants expect an object to remain stable if a significant portion of its surface is in contact with the support. It is at this age that most children learn to sit with support or become self-sitters, so that they are more likely to be seated in high-chairs, and to have the opportunity to deposit objects on surfaces and to learn that bottles, cups or toys tend to fall to the ground unless a significant portion of bottom surfaces is supported (Baillargeon et al., 1992). However, they can still show difficulties until the age of 9.5 months to understand that other features such as the mass distribution of an object is critical to determine whether a support is appropriate or not (Baillargeon & Hanko-Summers, 1990).

In broad terms, these results indicate that knowledge about the physical world – namely, mechanical knowledge – can be acquired relatively early in childhood and can continue to grow over the time, even during adulthood[5]. After all, even adults can learn how to better use a hammer by understanding that the position of the grip on the handle modifies the strength of percussion according to the lever principle (i.e., powerful percussion if the handle of the hammer is grasped at its basis versus precise percussion if the handle is grasped close to the head of the hammer; see Osiurak, 2014). In fact, mechanical knowledge is never completely accurate, and can be the basis for some "magical" beliefs such as thinking that *any* amount of contact between an object and a support is sufficient for the object to be supported. Of course, these "magical" beliefs can be improved with experience. For instance, Bril, Rein, Nonaka, Wenban-Smith, and Dietrich (2010) investigated stone knapping in novices and experts. They observed that experts' flacking success was far higher as compared to novices'. The reason is that the kinetic energy generated by novices was greater than what was required to detach flakes. In addition, Bril et al. (2010) observed that experts' bodily movements showed great variation, yet were appropriate when related to task requirements (see also Biryukova & Bril, 2008). In broad terms, experience plays a key role in the progressive acquisition of the key functional parameters of a given task (i.e., mechanical knowledge), more than in the learning of specific motor movements (for discussion on this aspect, see Osiurak & Badets, 2016). Given that many activities are gender-determined, it could also be hypothesized that the role of experience in acquisition of mechanical knowledge is influenced by gender. This gender hypothesis has been confirmed in semantic memory studies, indicating that males are more familiar with tools than females (e.g., Albanese, Capitani, Barbarotto, & Laiacona, 2000; Capitani, Laiacona, & Barbarrotto, 1999; Laiacona, Barbarrotto, & Capitani, 1998). However, with regard to mechanical knowledge, this remains to be demonstrated, notably because previous studies investigating mechanical problem solving in adults have failed to find such a gender effect (e.g., Osiurak et al., 2009).

Trial-and-error strategies

As discussed just above, we can sometimes engage in tool making activities while we do not possess the knowledge allowing us to actually solve the physical problem given. This is for

[5] In this respect, mechanical knowledge can be viewed as a form of non-declarative "crystallized" knowledge. Therefore, mechanical knowledge can be improved at any age, even if the amount of new information to be learned naturally decreases with age because of experience.

instance the case when we give a TV set a whack because it begins to dysfunction. We generally do so because we do not have knowledge about how a TV set works. Similarly, we can try to build a bridge and realizes that our bridge is not solid enough to support a single individual. This can arise because we did not fully understand the principle of bridge. Regardless, it is very likely that this experience will lead us to build a better bridge the next time. Interestingly, even if mechanical knowledge is not completely accurate, they seem to be fundamental to allow us to engage in activities. As discussed just above, evidence supports this assumption.

A recent study compared the strategies followed by left brain-damaged patients with apraxia of tool use and healthy controls in a mechanical problem-solving task (Osiurak et al., 2013a). Results indicated that the control group with higher performance selected spontaneously the appropriate tools so as to perform the mechanical actions intended. The control group with lower performance followed trial-and-error strategies, leading them to use irrelevant tools to interact with the problems, and sometimes to find the solution. Their solutions were not complete but at least partially complete, so that the interactions enabled us to improve the solutions initially generated. Interestingly, left brain-damaged patients did not follow trial-and-error strategies, spending a considerable time exploring visually the problem and the tools independently. These findings demonstrate that technical reasoning is a dynamic process, which can continuously be improved through our activities with the physical world. However, when mechanical knowledge is lacking, we can be stuck on the problem, being unable to initiate the least mechanical action.

Role of planning skills

It is commonly assumed that the ability to find solutions in new problem situations puts a heavy demand on prefrontal/executive functions (Miyake et al., 2000; Norman & Shallice, 1986; Shallice & Burgess, 1996). However, this is not always true. For instance, patients with frontal lobe lesions/dyexecutive syndrome are not impaired to solve mechanical problems (Goldenberg & Hagmann, 1998b; Goldenberg & Spatt, 2009; Goldenberg et al., 2007). In addition, the ability to solve these problems is not associated with scores on executive function tasks (Hartmann et al., 2005; Jarry et al., 2013). This suggests that the ability to face new situations is not the preserve of executive functions, particularly when the problem to be solved puts a heavy demand on the understanding of mechanical actions. In this case, technical reasoning skills (left inferior parietal cortex) might be critical, but not executives functions (prefrontal cortex).

Having said this, we are not denying that some executive functions such as planning skills can play a key role in the making step. For instance, if we intend to build a bridge, we can use technical reasoning to decide that a wooden board is a good solution. However, at this point, we can also realize that something is needed to attach it on each bank of the river. Again, technical reasoning is needed to envisage a solution, such as stakes. This also implies to make holes within the wooden board, perhaps by using a drill. *Intoolligence* assumes that many technical solutions can be generated by technical reasoning, and these solutions can be nested. In this context, the role of planning skills is to reorganize the sequence of actions in a coherent and economical way, perhaps by beginning to go get all the materials needed, then, by making the holes, and so on. This is precisely what is assessed by the Tower of London, which is a classical test of planning skills consisting in reproducing a configuration of balls with the lower number of moves (Shallice, 1982). Nevertheless, like semantic memory, planning skills are not involved in the generation of mechanical solutions per se.

Role of affordance perception and motor control

No one, so far as we know, has suggested that specific motor programs are stored to make a tool or to build a construction. Yet, these activities can require a vast repertoire of fine movements, and a high degree of motor coordination. So, it is again surprising to consider that tool use needs manipulation knowledge if we accept that very complex motor actions such as those occurring during construction can be performed without it. This is why *Intoolligence* assumes that affordance perception and motor control (dorsal fronto-parietal network) are independent of the nature of the activity carried out. When we make something, we have to move tools and objects according to a specific making plan. So, we need to perceive the appropriate affordance, and to control our motor production in order to perform the movements appropriate. The problem is strictly the same as when we use tools, or even when we move objects (Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Osiurak, Roche, Ramone, & Chainay, 2013b; see also Osiurak & Badets, 2016)[6].

Cognitive step 2: Use

> Strictly speaking, nothing is a tool except during use. The essence of a tool, therefore, lies in something outside the tool itself. (Butler, 1912/1951, p. 121)

Because of cumulative technological culture, we live in a world where the distance between the maker and the user is sometimes considerable. It is a fact: Humans have the propensity to simplify the interactions they have with the environment. We press buttons to open/close the garage door, to use our smartphones, and so on. In many of these instances, we do not know or understand the underlying physical principles. In many others, we are even not aware during the use that we are using some tools or technologies. However, in some cases, as suggested by Butler (1912/1951) we need to reason to complete the activity effectively. In this section, we present how we redefine tool use by breaking it into three different modes of use that characterize our interactions with tools and technologies: Assistive tool use, arbitrary tool use and free tool use. For each mode, we will discuss the potential cognitive processes involved.

Assistive tool use

This mode of use corresponds to that with the greatest gap between the maker and the user. More particularly, in this mode, there is no need, for the user, to conceive the use. This category also encompasses what is usually called "construction". This can be a road, for instance, or a house, a heating system, a table or a chair. These tools put great cognitive demands (i.e., technical reasoning) on the maker at the moment of their making. However, once made, anyone (including the user) can use them without mentally making them again, as in the farmer example, where he can become unaware of using his porch several days after making it. In fact, assistive tool use is only based on the individual's ability to perceive the tools' action possibilities, namely, affordances (e.g., the walk-ability for a road, the sit-ability for a chair; see Osiurak & Badets, 2016; Osiurak et al., 2010). Just look around you to have a pretty

[6] In this section, we have stressed the key role played by technical reasoning in the making step. We also discuss the importance of semantic memory, planning skills, and affordance perception/motor control. Nevertheless, tool making can also require additional cognitive functions (e.g., visuo-constructive abilities). In fact, almost all the cognitive functions can be involved in this step as well as in the use step, so we will not discuss them further, because of their secondary role.

good snapshot of the number of instances of human assistive tool use. Note also that there is no clear instance of nonhuman assistive tool use, except perhaps the building of nests.

Arbitrary tool use

As assistive tool use, there is a gap between the maker and the user in that the user is generally unable to understand the underlying mechanical actions. Nevertheless, unlike assistive tool use, arbitrary tool use requires additional cognitive skills because the user is not as "passive" as for assistive tool use. Arbitrary tool use can concern, for instance, smartphones, computers or calculators. This category encompasses cognitive tools involving the use of an interface (e.g., a keyboard) to work, but some physical tools can also be included within this category (e.g., washing machine, hairdryer). Car driving also falls within this category. More generally, arbitrary tool use corresponds to all these tools or technologies for which the user has no choice during the use because of physical constraints imposed by the maker. We cannot do otherwise than pressing buttons to switch on/off the light, or to open/close the garage door. Similarly, we cannot do otherwise than using the steering wheel and the lever to shift gear. This differs from free tool use (see below) for which the user possesses a certain level of freedom in their selection and application. While the maker is able to understand how this interface is connected to the system, most of the users only learn the arbitrary relationships between the effect expected and the motor action. Note that the maker also needs to learn these arbitrary relationships so that someone can be a better maker than user and vice versa (e.g., the stringed-instrument maker versus guitar player distinction).

As for assistive tool use, the perception of action possibilities/affordances remains the only way people have to interact with tools (e.g., the press-ability of a key). Nevertheless, the learning of the arbitrary relationships can be supported by procedural memory, notably when a certain sequence of actions is required, such as in the use of musical instruments, typewriting, or the use of smartphones or credit cards. However, it appears unlikely that procedural memory is involved in the learning of singular actions based on contingencies, such as pressing a button to switch the light on/off. In this case, more "archaic" cognitive processes could play a key role, such as associative learning, namely, the ability to learn contingencies without understanding the underlying causes (see Penn & Povinelli, 2007; Penn, Holyoak, &

Povinelli, 2008). Future research is needed to specify this aspect. Importantly, although some animals can use “arbitrary tools” made by humans, there is no evidence of nonhuman arbitrary tool use.

Free tool use

Here, there is no gap between the maker and the user in that the user needs to conceive the action the tool has to perform before using it. This category mainly includes physical tools such as knives, hammers or toothbrushes[7]. Thus, when an individual intends to cut a tomato, she needs to select the appropriate knife to do so. As discussed so far, the use of this category of tools – namely the category of tools that is the most commonly studied – might be support by technical reasoning, because the user needs to reason about the underlying mechanical actions in order to use these tools appropriately. So, unlike arbitrary tool use, free tool use is not based on procedural learning, because the use is not arbitrary but constrained by the understanding of physical laws. *Intoolligence* assumes that to use tools freely, we need first to mentally make them, by using technical reasoning. However, once the mental image of the motion of the tool is made, this image is used to perceptually control the production (Osiurak & Badets, 2016). If someone intends to pound a nail, the technical reasoning skills can lead him to the solution of using a hammer. So, he will represent the mechanical action involving the motion of the hammer relatively to the nail. Then, this is this mental image that will constrain the perception of the appropriate affordances as well as control the motor production during the use.

New avenues

Intoolligence aims to simplify the communication between scholars, and between scholars and students interested in the cognitive bases of tool use and technology. In this respect, it can also be fruitful to spur future research on the topic. In this section, we conclude by opening new avenues.

[7] In fact, any object or tool can fall within this category. For instance, someone can bring a car closer to create shade, while picnicking; or getting an old TV or heating system to use it as a seat in the living room. In all these situations, the individual needs to mentally make the tool to solve a physical problem. However, some of these tools can work by themselves, even when we are not aware of it. In this case, they fall within the category of assistive tool use. Likewise, some tools cannot be used other than using their interface. In this case, the use is considered as arbitrary.

First, *Intoolligence* assumes that the key cognitive process underlying human tool use and technology is technical reasoning. The corollary is that technical reasoning could play a fundamental role when someone learns new mechanical actions, by observing another individual using/making a tool or building a construction. This is at odds with the classical view, for which motor representations are central for social observation or learning, as suggested by the theories developed based on the discovery of the so-called mirror neurons (for discussion, see Gallese, Gernsbacher, heyes, Hickok, & Iacoboni, 2011). The technical reasoning hypothesis for social learning can also open new avenues for the understanding of complex phenomena of social transmission, such as cumulative technological culture. One of the major hypotheses is that this phenomenon is supported by the human ability to share intentions (Tomasello, Carpenter, Call, Behne, & Moll, 2005; Tomasello et al., 1993). However, cumulative performance can be observed without direct social interactions, when individuals only observe the results of the action performed by predecessors (Caldwell & Millen, 2009; Morgan et al., 2015; Zwirner & Thornton, 2015). In a way, technical reasoning skills could play a key role in cumulative technological culture, by allowing individuals to understand and learn the mechanical actions performed by predecessors. Evidence supports this hypothesis (Osiurak et al., 2016).

Second, *Intoolligence* suggests that common cognitive processes could be in charge of both tool using/making and construction. This aspect is interesting because the issue of the cognitive bases of human construction has been largely ignored so far. A significant number of studies have been conducted to explore tool use skills in brain-damaged patients. By contrast, there is no study aiming to investigate how people are able to build construction as well as to determine whether a link exists with tool use skills. This issue can also be explored in developmental psychology. *Intoolligence* posits that both abilities should develop conjointly. Finally, we have proposed that our understanding of how the physical world is based on the acquisition of mechanical knowledge. By doing so, we have focused on mechanical actions underlying tool making and construction. However, the development of our technology also derives from the mastery of chemical, electronic or electric principles. So, a fundamental issue for future research is whether these different aspects share the same neurocognitive bases, what we have called mechanical knowledge.

Third, *Intoolligence* posits a clear-cut, functional dissociation between technical reasoning and semantic memory. While the former is critical for understanding mechanical actions involved in tool use, tool making and construction, the latter is considered here as useful for getting information from episodic memory in an organized way. This proposal differs from the classical conception of semantic memory, which has led to key results such as the distinction between living and nonliving things and, more importantly, the distinction between manipulable (e.g., tools) and non-manipulable nonliving things (e.g., vehicles, furniture; Laiacona, Capitani, & Barbarotto, 2000; Warrington & McCarthy, 1987). These findings may appear at first sight to be inconsistent with a key hypothesis from *Intoolligence*, namely, technical reasoning supports the ability to use/make any categories of nonliving things. However, the aforementioned dissociations have been reported in tasks using pictures and words, and not on tasks requiring actual use and making. So, *Intoolligence* predicts that even if these dissociations can be reported in semantic tasks, they should not be linked to real performance in tool use/making or construction. Should this prediction be correct, it would offer new insights into the functional role of semantic memory in tool use.

Fourth, we can wonder whether *Intoolligence* is suited for the study of animal tool use. Our opinion is yes. Particularly, this framework allows us to escape from the emphasis placed on manipulation. As mentioned, Beck (1980) himself stressed that any definition of tool use is not biological distinctness. This warning has not received sufficient attention so that the literature on animal tool behavior suffers from an important distortion consisting in interpreting all tool behavior in terms of hominid evolution (for discussion, see Hansell & Ruxton, 2008). The consequence is that any animal showing tool behavior becomes suddenly a new potential candidate for understanding human tool use, joining the very “exclusive club of tool users” (e.g., Breuer, Ndoundou-Hockemba, & Fishlock, 2005; Hart, Hart, McCioy, & Sarath, 2001; see Hansell & Ruxton, 2008). Others have criticized the anthropocentrism (Shettleworth, 1998) and arbitrariness (Hansell, 1987) of definitions of tool use. Simply, this framework can be useful for better comparing animal versus human tool use, by focusing either on the making step or on the use step, without paying a special attention on tool use as if this behavior relies on specific cognitive skills.

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Table 1. Definitions of tool use, tool making, and construction behavior from Shumaker et al. (2011).

Label	Definition
Tool use	"The external employment of an unattached or *manipulable attached* environmental object to alter more efficiently the form, position, or condition of another object, another organism, or the user itself, when the user holds *and directly manipulates* the tool during *or prior* to use and is responsible for the proper and effective orientation of the tool." (p. 5)
Tool making	"Structural modification of an object or an existing tool by the user or a conspecific so that the object/tool serves, or serves more effectively, as a tool." (p. 11)
Construction	"Two or more tools and/or objects physically linked to make a functional, semipermanent thing that, once completed, is not held or directly manipulated in its entirety. A Construction itself is therefore *not* a tool. Nor is it tool manufacture, because the product is not a tool." (p. 19)

Table 2. The unified, *Intoolligence* framework for the cognitive study of human tool use and technology

Cognitive process	Neural basis	Cognitive step			
		Mental making	Use		
			Assistive	Arbitrary	Free
Technical reasoning (key process for mental making)	Left inferior parietal cortex	***			(*)
Semantic memory (organized search within episodic memory)	Temporal lobes, particularly the left	§			
Planning	Prefrontal cortex	§			
Affordance perception and motor control	Dorsal frontoparietal network	*	*	*	*
Procedural memory	Fronto-striatal network			**	
Associative learning	Not specified			**	

Note. The degree of involvement is represented by the number of asterisks. (*) means that technical reasoning is not involved per se during free tool use, but is necessary to generate the mental representation of the action to perform with the tool as well as in the perceptual control during use. § means that the process is involved during mental making although it is not the key process allowing mental making. The potential neural basis is also listed. This can be useful for generating predictions. For instance, patients with selective damage to the left inferior parietal cortex should encounter difficulties for mental making (i.e., physical making, construction, selection and fixing) and free tool use, but not for arbitrary tool use. By contrast, patients with damage to the fronto-striatal network should be mainly impaired when asked to use "arbitrary tools". Further explanations are given in the text.

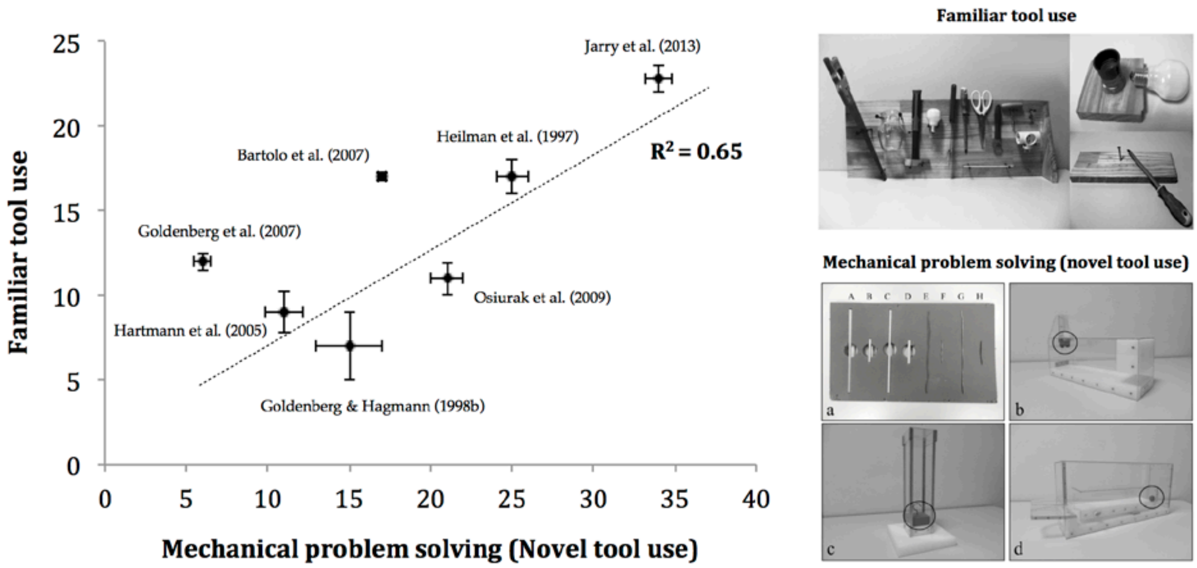

Figure 1. Link between familiar tool use and mechanical problem solving. Familiar tool use refers here to the use of everyday tools such as a hammer or a pair of scissors. The clinical test assessing the ability to use familiar tool use can consist in asking patients to select among several tools the most appropriate one to perform a given task (e.g., pounding a nail; top left panel). Mechanical problem solving can be assessed by asking patients to extract a target out from a box. To do so, several novel tools can be presented, so that patients have to select the most appropriate one (bottom left panel). Interestingly, a strong relationship has been reported between these tasks in left brain-damaged patients (right panel). The boxplot represents the strength of these relationships. Each point refers to a study where both left brain-damaged patients and healthy controls were assessed on both tasks. Here the patients' deficit is expressed in terms of percentage of impairment as compared to healthy controls ($M_{Controls}$–$M_{Patients}$). The total number of patients concerned by these studies is 141. Bars represent the number of patients for each study (e.g., *n* = 5 in Bartolo et al., 2007; *n* = 42 in Goldenberg & Hagmann, 1998b).

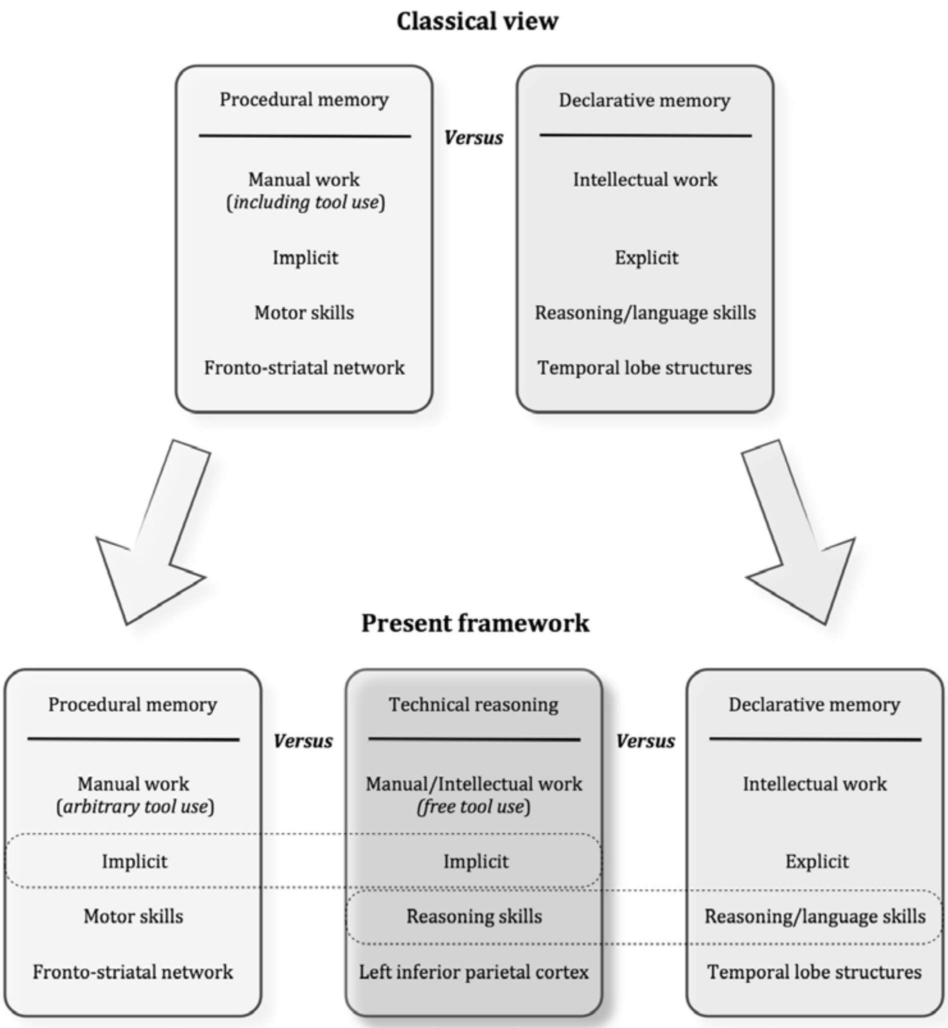

Figure 2. Role of procedural memory in tool use. Influential cognitive meta-theories posit that there are two main memory systems, namely, procedural memory and declarative memory. In this frame, tool use is commonly viewed as an instance of manual work, based on the learning of motor skills and, as a result, procedural memory. The present framework, *Intoolligence*, proposes an update of this view, by positing that procedural memory is involved only in arbitrary tool use. By contrast, free tool use needs technical reasoning. Interestingly, technical reasoning skills share with procedural memory the "implicit" aspect, and with declarative memory the "reasoning" aspect. Further explanations are given in the text.

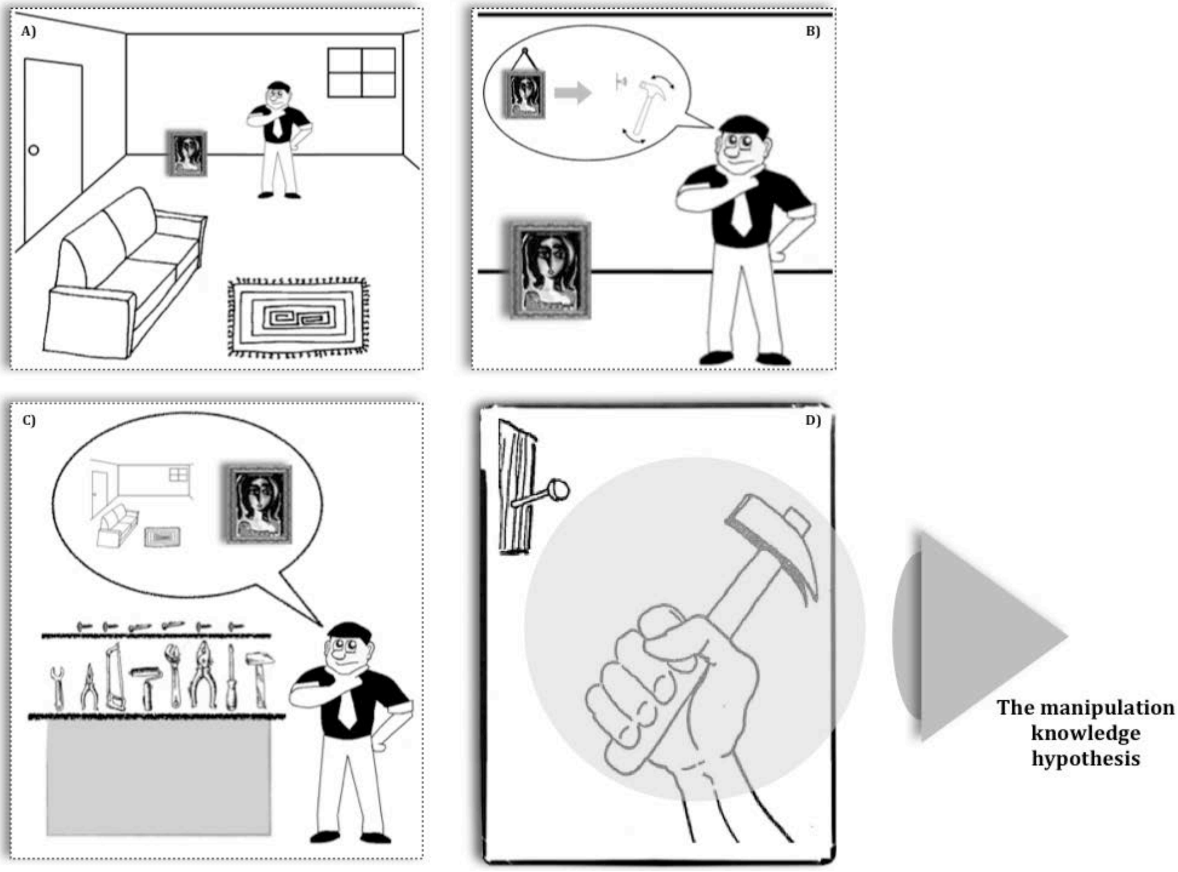

Figure 3. Epistemological limitation of the manipulation knowledge hypothesis. Imagine someone who intends to hang up a painting on a wall (see Caruana & Cuccio, in press; Osiurak, in press). At the beginning, nothing is present except the wall and the painting. So, he needs to reason about which mechanical action can be appropriate to do so (Panel A). Perhaps he can decide to drive a nail into the wall, by using a hammer (Panel B). This requires him to take into account the physical object properties of the wall (e.g., solidity) but also the painting (e.g., the weight). At this step, there is no manipulation: He is only mentally making his tool. Given that nothing is present, he has to go to his workshop to go get the hammer and nails. While in the workshop, this individual can keep on reasoning about the appropriateness of the nails found relatively to the painting and the wall, which are now absent (Panel C). Again, there is still no manipulation. Imagine that he is satisfied by the tools and objects found in the workshop. He comes back to his living room, and can now begin to pound the nail (Panel D). This is the moment where manipulation comes into play. So, if we ignore all the steps described here before manipulation, we may have the feeling that the use is only a matter of how to manipulate the hammer correctly, as suggested by the manipulation knowledge hypothesis. However, if we accept that the use began well before the manipulation, it becomes clearer that tool use cannot be systematically restricted to mere manipulation. Instead, it appears that we could use tools in order to solve physical problems as assumed by *Intoolligence*.