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François Osiurak

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WHAT NEUROPSYCHOLOGY TELLS US ABOUT HUMAN TOOL USE?

THE FOUR CONSTRAINTS THEORY (4CT): MECHANICS, SPACE, TIME, AND EFFORT

François Osiurak

University of Lyon, France

Correspondence concerning this article should be addressed to:

François Osiurak

Laboratoire d'Etude des Mécanismes Cognitifs

Université Lumière Lyon 2

5, avenue Pierre Mendès-France

69676 Bron Cedex, France

Email: Francois.Osiurak@univ-lyon2.fr

Tel: +33 (0) 4 78 77 43 95

ABSTRACT

Our understanding of human tool use comes mainly from neuropsychology, particularly from patients with apraxia or action disorganization syndrome. However, there is no integrative, theoretical framework explaining what these neuropsychological syndromes tell us about the cognitive/neural bases of human tool use. The goal of the present article is to fill this gap, by providing a theoretical framework for the study of human tool use: The Four Constraints Theory (4CT). This theory rests on two basic assumptions. First, everyday tool use activities can be formalized as multiple problem situations consisted of four distinct constraints (mechanics, space, time, and effort). Second, each of these constraints can be solved by the means of a specific process (technical reasoning, semantic reasoning, working memory, and simulation-based decision-making, respectively). Besides presenting neuropsychological evidence for 4CT, this article shall address epistemological, theoretical and methodological issues I will attempt to resolve. This article will discuss how 4CT diverges from current cognitive models about several widespread hypotheses (e.g., notion of routine, direct and automatic activation of tool knowledge, simulation-based tool knowledge).

KEY WORDS: Action Disorganization Syndrome; Apraxia; Motor Simulation; Technical Reasoning; Tool Use

WHAT NEUROPSYCHOLOGY TELLS US ABOUT HUMAN TOOL USE?

THE FOUR CONSTRAINTS THEORY (4CT): MECHANICS, SPACE, TIME, AND EFFORT

1. INTRODUCTION

Tool use skills are one of the defining features of the human species. These skills have enabled, and still enable us to modify our way of interacting with the world, leading to significant environmental changes. Just think about what the place where you are looked like 100 years ago and you will have a pretty good snapshot of it. So, a fundamental issue is, what are the cognitive bases of human tool use? Until recently, this issue has received very little attention from psychologists (Massen 2013), so it would be very difficult for a student interested by tool use to find a comprehensive theoretical framework on this topic. Of course, this is not to say that no synthesis has been provided. Nevertheless, even if these rare attempts offer thorough overviews of the underlying cognitive processes (e.g., Baber 2003; Vaesen 2012), they do not offer an integrative theoretical framework aiming to resolve a certain number of well-identified issues. The goal of the present article is to fill this gap, by providing a theoretical framework for the study of human tool use, namely, the Four Constraints Theory (4CT). This theory rests on two basic assumptions. The first is that everyday tool use activities can be formalized as multiple problem situations consisted of four distinct constraints (mechanics, space, time, and effort). The second is that each of these constraints can be solved by the means of a specific process (technical reasoning, semantic reasoning, working memory, and simulation-based decision-making, respectively). Besides presenting neuropsychological evidence for 4CT, this article shall also address a certain number of epistemological, theoretical and methodological issues I will attempt to resolve. In this way, 4CT will be compared to several current models. I hope that this article will help the readers in their efforts to better understand the cognitive bases of human tool use.

2. DEFINITIONS

2.1. TOOL USE

Tools can be defined as any handheld physical object that is used to make changes to other objects of the environment. For instance, a nail is not a tool, but the hammer used for pounding it into a wooden board is. It is also common to name “object” the recipient of the tool’s action (e.g., nail; Goldenberg and Hagmann 1998; for discussion on the notion of tool use, see Osiurak et al. 2010).

2.2. APRAXIA

Most of our understanding about human tool use comes from left brain-damaged (LBD) patients with apraxia, a disorder of skilled movement and tool use (De Renzi 1989). Apraxics can show difficulties to imitate meaningless postures or produce meaningful, symbolic gestures such as waving goodbye (see Goldenberg 1995, 1999, 2013a; Goldenberg et al. 2003). However, this article focuses only on patients with apraxia of tool use. When asked to light a candle, those patients can light the candle correctly but then put it to the mouth in an attempt to smoke it. Apraxia of tool use is generally assessed by asking patients to demonstrate how to use a familiar tool without holding the tool (pantomime), while holding the tool (single tool use) or by using the tool with the corresponding object (real tool use)¹. Apraxia of tool use results from posterior lesions of the left hemisphere (see Goldenberg 2013a).

2.3. ACTION DISORGANIZATION SYNDROME

The term “action lapses” describes the failures occurring in multi-step, routine everyday activities in neurologically intact individuals (Norman 1981; Reason 1979). When these action lapses go outside the boundaries of those normally found, making the activity disorganized, the term “action disorganization syndrome” (ADS) is preferred (Humphreys

and Forde 1998; Morady and Humphreys 2011; Schwartz 1995). This disorder was initially seen as a hallmark of frontal lobe dysfunction (Penfield and Evans 1935; Schwartz et al. 1991). However, studies have challenged the specificity of ADS to frontal lobe damage, suggesting that it might be associated with general decreases in cognitive resources after brain damage (Buxbaum et al. 1998; Schwartz 1995; Schwartz et al. 1998). Clinically, ADS can be assessed by asking patients to perform everyday routine activities either with all and only the target tools and objects, or in the presence of related but inappropriate tools or objects (i.e., distractors). Patients can also be asked to carry out two activities concomitantly (preparing both a lunchbox and a schoolbag; e.g., Buxbaum et al. 1998; Morady and Humphreys 2011; Schwartz et al. 2002).

3. CURRENT THEORETICAL MODELS OF HUMAN TOOL USE

3.1. THE COGNITIVE MODELS OF APRAXIA

Cognitive models of apraxia are organized around the distinction between a production and a conceptual system (Bartolo et al. 2007; Binkofski and Buxbaum 2013; Buxbaum 2001; Cubelli et al. 2000; Heilman et al. 1982; Rothi et al. 1991). The production system is dynamic and allows the adaptation of movements to external constraints in function of the representation formed within the conceptual system (Buxbaum 2001; Heilman et al. 1982, 1986). It encodes egocentric relationships between the user and the tool. In line with the famous dual-stream hypothesis (e.g., Milner and Goodale 2006), this system is located within the dorsal and even dorso-dorsal stream, within superior parietal lobes (Buxbaum and Kalénine 2010).

The conceptual system is generally divided into two kinds of knowledge. The first is semantic knowledge about tool function, containing information about the conventional use of familiar tools (i.e., for which purpose, in which context and with which object; Hodges et al.

2000). Therefore, this knowledge encodes allocentric relationships between tools and objects. It relies on the ventral stream and, more particularly, on the left anterior temporal lobes (Goldenberg and Spatt 2009; Hodges et al. 2000). The second is sensorimotor knowledge about tool manipulation (Buxbaum 2001; Rothi et al. 1991). This knowledge contains the features of gestures which are invariant and critical for distinguishing a given tool gesture from others. Therefore, it encodes egocentric, user-tool relationships. The neuroanatomical locus of damage is the left inferior parietal lobe.

3.2. THE THEORY OF CONTROLLED AND AUTOMATIC ACTION SELECTION

One of the most prevailing accounts of ADS is the theory of controlled and automatic action selection (hereafter called the dual-systems theory; Cooper and Shallice 2000, 2006; Norman and Shallice 1986). This theory describes the interaction between two systems. The first one is the supervisory attentional system (SAS), which is involved in the control of non-routine activities. It is synonymous with the concept of executive control and is supported by prefrontal lobe structures (see Cooper and Shallice 2000; Shallice and Burgess 1991). This system plays a critical role in “dealing with novelty or overcoming instinctive behavior to act in a socially appropriate manner” (Humphreys and Forde 1998). Thus, patients with dysexecutive syndrome can be influenced by environmental prompts, leading them to pick up and use tools and objects that are clearly not appropriate to the task at hand (i.e., utilization behavior; Lhermitte 1983; Lhermitte et al. 1986; Shallice et al. 1989). Patients can also meet difficulties in everyday life activities, particularly when the number of steps, sequencing constraints and/or tools and objects presented simultaneously is relatively important (Schwartz et al. 1998).

The second system is the contention scheduling (CS), which is responsible for routine selection of action. The functions of CS might be performed by the basal ganglia (Norman and Shallice 1986) but its neural localization remains unclear (see Cooper 2002). The

selection is based on schemas, namely, relatively low-level actions such as opening a jar, spreading jam on bread, or preparing instant coffee. Schemas are goal-directed in that each schema has a goal that it achieves. In this frame, a goal is a condition that may or may not be satisfied by the world. The goal is satisfied when the condition is true of the world. Moreover, schemas are in lateral inhibitory competition, with the amount of competition depending upon the degree of overlap in the effector system requirements (e.g., we cannot use the hands for both opening a sugar packet and pouring hot water into a mug). Another requirement concerns the physics of the environment, which provides continuous feedback participating in the regulation of the activity (e.g., it is not possible to add sugar from a packet to a mug if the packet is not open before).

4. THEORETICAL AND EPISTEMOLOGICAL ISSUES

4.1. THE NOTION OF ROUTINE

The dual-systems theory is based on a basic distinction between routine and non-routine activities. The intriguing question is, what is a routine? Schwartz et al. (1991) observed a patient, HH, who developed ADS following frontal lobe lesions. The patient HH was examined over a 3-month period on two routine activities within a neuropsychological recovery ward (preparing instant coffee and brushing teeth). While HH initially committed many action lapses, he significantly improved over the assessment period. This longitudinal study questioned the role of SAS in routine activities given that the dual-systems theory does not predict that routine activities should be supported by SAS. Cooper (2002) offered an alternative by arguing that everyday actions assessed in clinical and experimental conditions tap a level of action beyond that which is routine. To support this view, he suggested that HH's recovery over the 3-month period reflects the progressive routinization of his behavior,

thereby implying that SAS is involved in clinical, everyday action tasks. He added that, by contrast, routine action, by definition, does not require SAS.

This alternative raises the following issue. If clinical everyday action tasks are inappropriate to assess routine activities (except perhaps after a period of routinization), how to test that SAS is unnecessary to carry out these activities. In addition, there is a contradiction here, because Cooper and colleagues have developed a computational approach of the functioning of CS only, in order to predict the behavior of patients with ADS (such as HH) in clinical, everyday action tasks (Cooper and Shallice 2000, 2006; Cooper et al. 2005). Yet, if SAS is involved in these clinical tasks before the progressive routinization of the behavior, these tasks are not suited for examining the specific role of CS. In sum, the issue is still to specify what is a routine, how to assess it clinically and, therefore, how to demonstrate that routine activities are only based on automatic processes (for a similar viewpoint, see Goldenberg 2013a).

4.2. THE NEED TO GET TOOLS AND OBJECTS

When we engage in everyday activities, all the needed tools and objects are not at hand in the workspace, forcing us to get them either before or during the activity (i.e., the space constraint²). In addition, it is very frequent that we decide to modify our tool choice during the activity, also forcing us to leave the workspace to get the new tool option. The workspace is also rarely clear, with a great number of irrelevant tools and objects (i.e., distractors), and more particularly at the beginning when no relevant tool or object is present. In the latter case, the question is, how can automatic activation of schemas guide the behavior given that no relevant element is present? Models commonly overlook this fundamental question, as if their only purposes were to explain how people organize their activity with all the needed tools and objects present. However, to be viable, any theory of human tool use must account for how people solve the space constraint.

4.3. THE EXPERIMENTER'S EXPECTATIONS

One of the most frequently tasks used to assess apraxia is the demonstration by pantomime. Significant evidence has shown, however, that LBD patients perform better when asked to actually carry out the action (real tool use; Clark et al. 1994; Goldenberg et al. 2004; Hermsdörfer et al. 2006; Lesourd et al. 2013). To explain this difference, it has been suggested that visual feedback from the corresponding object as well as haptic and kinesthetic feedback from the manipulated tool might provide additional cues facilitating the access to sensorimotor and semantic knowledge (e.g., Bozeat et al. 2002). This interpretation is based on the assumption that the mere observation of a tool or an object *directly* activates representations about its usual use. As a result, the presence of additional information enhances activation of these representations, particularly when they are inaccessible, defective or incomplete. A potential limitation, however, is that the performance is interpreted with regard to the experimenter's expectations, which is centered on the usual use.

This view ignores that when subjects are assessed, they form a representation of the experimenter's expectations. When a tool is presented in isolation, the experimenter's expectations can be ambiguous. After all, the only presence of a knife can suggest different usages (peeling a fruit, cutting bread, opening an envelope). In this case, the additional presence of bread can help the subject to understand the experimenter's expectations. Nevertheless, if an individual demonstrate how to peel a fruit in a pantomime condition, his performance might be considered as impaired because this is not the action expected by the experimenter. This is not to say that the difference observed between the pantomime condition and real tool use can always be interpreted as resulting from an ambiguity with regard to the experimenter's expectations. Nevertheless, it is important not to ignore that showing how to use a tool presented in isolation requires a certain kind of social knowledge to fit experimenter's expectations.

4.4. *THE MULTIPLE ROUTES FOR ACTION*

A significant body of evidence has indicated that semantic memory and real tool use can be impaired independently from each other (Bartolo et al. 2007; Bozeat et al. 2002; Buxbaum et al. 1997; Forde and Humphreys 2000; Goldenberg and Spatt 2009; Hodges et al. 2000; Lauro-Grotto et al. 1997; Negri et al. 2007a; Osiurak et al. 2008b, 2009, 2011; Silveri and Ciccarelli 2009), suggesting that semantic memory is neither necessary nor sufficient for tool use. The ability to use tools despite semantic deficits can be explained by the preservation of sensorimotor knowledge. This is the famous multiple routes for action (e.g., Buxbaum 2001; Rothi et al. 1991). However, sensorimotor knowledge is supposed to contain information about the usual manipulation of tools (egocentric, user-tool relationship), and not about the objects with which they are usually used (allocentric, tool-object relationship). So no compensation should be possible. More generally, this theoretical issue questions the validity of the multiple-routes-for-action assumption, which leads authors to consider that each kind of knowledge can support the function of the other. Perhaps a good way to bypass such theoretical issues would be to reject the idea that the different kinds of knowledge involved in tool use can be multifunctional.

4.5. *NOVEL TOOL USE*

Since the last two decades, there has been a growing interest in the ability of apraxic patients to solve mechanical problems. These tasks can require participants to select among several novel tools the one appropriate for bringing a target out from a box (Jarry et al. 2013; Osiurak et al. 2013a) or for lifting a cylinder (Goldenberg and Hagmann 1998; see **Figure 1**). To solve these problems requires mechanical knowledge that is not linked with any specific tool representation, given that the tools given are novel. According to the dual-systems theory, SAS is necessary to solve novel situations. However, this system is not thought to contain specific information, but can only regulate the functioning of overlearned representations.

Cognitive models of apraxia, including the most recent ones, ignore this kind of knowledge because it would be involved only in rare situations (e.g., Binkofski and Buxbaum 2013; Buxbaum 2001; Rothi et al. 1991). It has been nevertheless proposed that this knowledge might be a component of sensorimotor knowledge associated with motor imagery (Buxbaum 2001; Sirigu et al. 1991). This proposal is delicate because mechanical knowledge is supposed to help people to determine mechanical transformations between tools and objects (allocentric relationship) whereas sensorimotor knowledge is thought to contain information about the usual manipulation of a tool (egocentric relationship). In sum, neither the dual-systems theory nor cognitive models of apraxia offer a satisfactory framework to integrate this knowledge.

< Insert Figure 1 about here >

5. THE FOUR CONSTRAINTS THEORY (4CT)

5.1. BASIC ASSUMPTIONS

4CT aims to overcome the aforementioned issues. The idea that the distinction between SAS and CS mirrors the distinction between novel and routine activities is delicate, notably because it remains difficult to define what is a routine and to know how to assess it (Goldenberg 2013a). In addition, in daily life, people have to constantly solve the space constraint before performing the activity per se. This makes even more delicate the idea that routines consist in organizing tool actions in the presence of all the target tools and objects. Therefore, it is important to model how people carry out everyday activities, without taking into consideration the notion of routine. Besides, the issue of how to use novel tools has been viewed as peripheral. This may appear surprising for authors in the field of developmental psychology, in which tool use is regarded as an instance of problem-solving situation supporting by mechanical reasoning skills (e.g., Beck et al. 2011; Mounoud 1996). Given that there is no reason that these skills acquired during the development have no more role to play

in adulthood, I also assume that these skills support both novel and familiar tool use, making them central to 4CT. Finally, the multiple-routes-for-action hypothesis is, by nature, irrefutable because each kind of knowledge can support the function of the other. So, 4CT proposes that each process is associated with only a specific function.

A schematic illustration of 4CT is displayed in **Figure 2**. This theory rests on two basic assumptions. First, everyday tool use activities can be formalized as multiple problem situations consisted of four distinct constraints (mechanics, space, time, and effort) imposed by the environment on the user. These problems emerge spontaneously because of the gap between the current state of the world and the user's desired state of the world. Second, each of these constraints can be solved by the means of a specific process (technical reasoning, semantic reasoning, working memory, and simulation-based decision-making, respectively). 4CT assumes that the processes supporting the solving of these constraints belong to the conceptual level of the activity.

- ***Mechanical constraint.*** Even if tools and objects are in the workspace of an individual, they do not perform mechanical transformations by themselves. So the role of the user is to be able to conceive of these transformations.
- ***Space constraint.*** Tools and objects are not directly available in the individual's workspace. Therefore, the role of the user is to bring them back in the workspace.
- ***Time constraint.*** During an everyday activity, a certain number of desired states (i.e., goals) have to be reached over time. Environmental feedback is not always available to drive the behavior. The role of the user is here to foresee the different desired states to facilitate the temporal organization of the activity.
- ***Effort constraint.*** The execution of any action generates a cost, which can be physical or time-based. The role of the user is to decide what is the best option.

< Insert Figure 2 about here >

At this point, two caveats need to be mentioned. First, this is not to deny that actions can be conceived by processes other than the four processes specified by 4CT. Consider the example of an apraxic patient attempting to cut a loaf of bread into pieces by using a spoon and then a fork. This example illustrates the use of a trial-and-error strategy, which can be followed when technical reasoning is impaired – but also, more generally, when people do not have the mechanical knowledge required to solve a mechanical problem. By doing so, the patient generates a conception of the tool action to be made, even if he meets difficulties to determine that the tool action is not effective. This strategy leads the patient to form a representation of what to do and to execute movements consistent with this representation. Consequently, it may be suggested that there is no need to develop a theory stressing the importance, for instance, of technical reasoning if “more basic processes”³ can also support the conception of tool actions. However, 4CT assumes that such “basic processes” cannot explain how people are able to perform everyday activities, which can sometimes include relatively long sequences of actions. In addition, the fact that patients with apraxia of tool use or ADS encounter difficulties to carry out everyday activities corroborates the idea that “more basic processes” such as trial-and-error (to attempt to achieve the intended mechanical transformations) or the use of the environment as external memory (to compensate for working memory deficits) are not sufficient to perform everyday activities in an effective way.

Second, whether people use the processes specified by 4CT or “more basic processes” to conceive actions, it is needed to execute movements in order to transform the current state of the world into the desired state of the world. Therefore, an additional system is required to enable the execution of the solutions generated at the conceptual level. This is the production system. Before addressing each of the aforementioned constraints in turn, I will present the production system.

5.2. THE PRODUCTION SYSTEM

Cognitive models of apraxia suggest that sensorimotor knowledge provides a processing-advantage, avoiding portions of the process from being reconstructed de novo with each experience (Buxbaum 2001; Rothi et al. 1991). Nevertheless, given that sensorimotor knowledge belongs to the conceptual level, an additional system is required to adapt the gesture to the environmental constraints. The sensorimotor knowledge hypothesis is subject to a certain number of limitations that will not be discussed here (see Osiurak et al. 2010, 2011; see also Goldenberg 2013a). Simply, whereas this hypothesis regards manipulation as central at the conceptual level, 4CT assumes that the conceptual level does not contain any sensorimotor information about tool manipulation. In a more parsimonious way, 4CT suggests that the role of the production system is to control motor behavior in order to transform the current state of the world into the desired state of the world, which is conceived at the conceptual level. This assumption is very close to what we previously called the reconstruction hypothesis (Osiurak et al. 2008a, 2009, 2010, 2011; see below for a refinement of this hypothesis).

The issue of how humans select among the multitude of body actions the appropriate one to perform a given action has been extensively discussed in the context of degrees-of-freedom problem introduced by Bernstein (1967). To solve it, he proposed that it is necessary to identify *dependencies within the motor system* that constrain or reduce the degrees of freedom that need to be independently controlled. The end-state comfort effect initially observed by Rosenbaum et al. (1990) is a good instance to illustrate it (see also Rosenbaum et al. 1992). People tend to take hold of an object in awkward way to permit a more comfortable final posture once the object is brought to its target position. In other words, the representation of the action (i.e., object's motion) constrains the goal posture and, as a result, the course of movements (Rosenbaum et al. 2001).

Given that whether an individual uses a tool or transports an object there is object's motion, the same rationale can be applied to tool use too (see Osiurak et al. 2013b; Rosenbaum et al. 1992). For instance, a hammer can be used to perform either power or precise actions, leading to grasp it either at the basis of its handle or close to its head, respectively. In this instance, the grip selection is based on the understanding of the lever principle, namely, the more the rotation point of the hammer is far from the point of percussion the more the hammer's impact strength is amplified. So if an individual understands this principle, he is able to form a representation of the correct motion of the hammer relatively to the nail. And, it is this representation that constrains the movements to be executed (**Figure 3**). Consistent with this, we recently (Osiurak and Badets 2014) demonstrated that when people intend to use a tool (e.g., opening pliers to move an object with a hand's closing action), they activate the tool-action representation (pliers' opening action) and not the hand-action representation (hand's closing action).

< Insert Figure 3 about here >

In sum, 4CT suggests that the production system is involved in any situations requiring the interaction of the body with the environment and is guided by the representation of the action conceived at the conceptual level (e.g., tool's motion). As mentioned above, the reconstruction hypothesis is very close to this assumption. This hypothesis has been formulated as an alternative to the sensorimotor knowledge hypothesis that assumes that stored sensorimotor knowledge is used to guide movements. Unfortunately, the reconstruction hypothesis can be misunderstood and viewed as suggesting that movement coordination is not flexible. In line with the notion of synergies (Latash et al. 2007), 4CT posits that the role of the production system is to flexibly coordinate the degrees of freedom of the different joint angles in order to execute movements consistent with the action to be performed (e.g., tool's motion). The corollary is that given that the representation of the action remains constant over

time, the production system is able to keep stable the action to be performed (e.g., tool's motion), while the properties of the system (e.g., joint angles) can vary. In line with this, van der Steen and Bongers (2011) had participants make pointing movements either with the index finger or with the index finger extended by rods (10, 20, or 30-cm length). They found that even if joint angles changed over the conditions (index finger and rods), the variability of the joint angles was used to keep the movement of the end-effector stable during the reaching action whatever the condition. Likewise, Nonaka (2013) studied the movement coordination in a tetraplegic patient who has practiced Japanese calligraphy with a mouth-held brush for over 25 years. He observed that task variables (e.g., brush pressure, brush angle) were kept invariant over different realizations of the task although joint angles fluctuated.

As mentioned above, the role of the production system is to control motor behavior in order to transform the current state of the world into the desired state of the world, which is conceived at the conceptual level. This may be misunderstood as the idea that the conceptual system is the basis for movement planning and the production system the basis for movement control as well as that both systems do not work in a dynamic way. 4CT does not assume this, but rather suggests that both movement planning and control are supported by the production system, and that both systems work together dynamically and interactively. Let me illustrate it with the aforementioned example of the use of a hammer. Evidence indicates that by wielding an unseen object (i.e., by dynamic touch), people are capable of perceiving its “hammer-with-ability”, on the basis of information extracted, such as the distribution of the mass (Wagman and Carello 2001, 2003). The extraction of this information can lead to two kinds of processes. Imagine an individual grasping a hammer and beginning to pound a nail with it. 4CT posits that the planning and control of the movements will be supported by the production system in line with the representation of the hammer's motion conceived by the conceptual system: The individual perceives in an anticipatory fashion the head of the

hammer striking the nail, and the role of the production system is to plan and control body movements in order to accomplish it. Imagine now that the action is relatively ineffective. The first process consists in modifying the execution to make it more consistent with the representation of the tool's motion (i.e., accommodation). For example, the extraction of information about the distribution of the mass can lead the individual to plan a new series of – perhaps more effortful – movements to be more consistent with the representation. The second process consists in using the information extracted to revise the conception of the action (i.e., assimilation). In this case, the individual can revise the a priori representation of the tool's motion and decide to change the position of its grip on the hammer. This change results from the re-application of the principle of lever in function of the new information extracted from wielding. Finally, this modification can also occur directly when the individual grasps the hammer for the first time, by anticipating that the grip is not correct and will not allow to perform the intended tool's motion. In broad terms, these examples illustrate that the conceptual system and the production system work together in a dynamic and interactive way.

5.3. THE MECHANICAL CONSTRAINT

4CT posits that the ability to solve mechanical constraints is supported by technical reasoning, which is consisted of two components: Mechanical knowledge and object-based knowledge (Osiurak et al. 2009, 2010, 2011, 2013a; for a similar view, see Goldenberg and Hagmann 1998; Goldenberg and Spatt 2009; Penn et al. 2008). A schematic illustration of this reasoning is displayed in **Figure 4**.

< Insert Figure 4 about here >

5.3.1. Mechanical knowledge

Mechanical knowledge (e.g., tracing, cutting, percussion, lever) is based on the understanding of opposition existing between properties. For example, understanding the

cutting action is equal to understanding that it is the relative opposition between one thing possessing the properties ABRASIVENESS+, HARDNESS+, and WIDTH- versus another possessing the properties ABRASIVENESS-, HARDNESS-, and WIDTH+. This knowledge is assumed to be abstract for two reasons. First, there is no overlapping between the physical reality and the technical reality. The same physical matter (e.g., glass) can possess distinct properties (resistant, sharp, transparent, etc.). Conversely, distinct physical matters (plastic, wood, metal, etc.) can have the same property (e.g., resistant). Moreover, the same physical matter does not always offer the property appropriate for a given action. For example, the lead of a pencil is friable when applied to paper but not to leather. Said differently, even if a physical matter can possess the properties suitable for a given mechanical action in a given, observable situation, the suitable nature of its properties is not absolute but necessarily relative to the situation. Second, if humans stored the properties of a given tool or object (e.g., friability of a lead of pencil) in an absolute manner, then they would not be able to transfer the mechanical actions they learn in a given situation to another one. However, one of the specificities of human tool use lies in the transfer ability⁴ (Leroi-Gourhan 1971; see also Penn et al. 2008).

5.3.2. Object-based knowledge

Mechanical knowledge is abstract and requires to be reified into the real world to select the appropriate tools and objects. Object-based knowledge is the basis for this reification. As suggested just above, it appears difficult to consider that object-based knowledge is stored in an absolute way. This would suppose that pencils are stored as friable or light, while the friability and lightness of a pencil necessarily depends upon the intended action and the given situation. Therefore, every object is stored in a relative manner on the basis of the different properties it possesses, allowing a certain degree of flexibility within object-based knowledge. More particularly, each object is made of matter possessing a certain number of properties

such as hardness, weight, shape and so on. When we experience a new object, we extract information about its different properties and store them in function of their intensity relative to previously acquired knowledge. The corollary is that object-based knowledge can be thought as a network with each object corresponding to a node between its different relative properties. Moreover, when an individual has to make a mechanical action, the relative intensity of each object's properties allow to test whether the potential tools and objects are appropriate to perform the transformation by the means of a comparison with the abstract opposition provided by mechanical knowledge.

The object-based knowledge hypothesis proposed here requires refinement, particularly with regard to the issue as to whether this knowledge is purely abstract, modality-specific or based on modal simulation⁵. In fact, the idea that knowledge might be stored in a relative manner must be viewed as a working hypothesis, which may open new ways of investigating tool use impairments in patients with apraxia of tool use. For instance, do these impairments result from either impaired object-based knowledge or mechanical knowledge? Said differently, are these patients unable to determine relative objects' properties? Or, are they able to do so but unable to test whether the information obtained is compatible with the representation of the action provided by mechanical knowledge?

5.3.3. The principle of dialectic

4CT posits that the technical reasoning and the production system are integrated into a dynamical process, hereafter called dialectical process (Osiurak et al. 2010). Imagine a cook who would like to eat a slice of bread with jam. Consider that all the needed tools and objects are within the workspace (see below for the space constraint). To eat his snack, our cook has to carry out a certain number of mechanical transformations (e.g., cutting, spreading). For the sake of clarity, only the sub-goal "slice of bread" will be considered. The problem our cook faces is that there is a gap between the desired state of the world (i.e., the goal; slice of bread)

and the current state of the world (a loaf of unsliced bread). In a way, the mechanical constraint our cook has to solve is to transform the current state into the desired state.

The dialectical process suggests that the problem emerges from the initial relationship between the cook and the current state. At this step, nothing prevents the cook from using the production system to perform body actions in order to make the intended transformation. The first movement of the dialectical process consists in getting out of this relationship to do technical reasoning. For example, our cook can use the mechanical knowledge “cutting”, which involves the opposition between one thing possessing the properties ABRASIVENESS+, HARDNESS+, and WIDTH- versus another possessing the properties ABRASIVENESS-, HARDNESS-, and WIDTH+. By using object-based knowledge, our cook can reify one of the elements of this abstract opposition into the invariant of the problem, namely, the current state of the world (i.e., the loaf of bread). Also by using object-based knowledge, he can also determine the free element of the opposition, that is, something that is ABRASIVENESS+, HARDNESS+, and WIDTH- relatively to the loaf of bread, to select the appropriate free element by probing the immediate workspace. However, even though he formed a representation of the mechanical transformation, it cannot occur without the intervention of the cook’s production system. This corresponds to the second movement of the dialectical process in that the representation of the mechanical transformation can now guide the course of his movements.

5.4. THE SPACE CONSTRAINT

5.4.1. Usage versus technique

Pre-historians have stressed that the technical evolution of all human societies is characterized by the ability to acquire a technique⁶ for a specific usage and to transfer it for another one (Leroi-Gourhan 1971). For instance, the same knife can be used to perform the cutting action in a wide range of usages (cutting a piece of wood, cutting bread, peeling a

fruit, opening letters, cutting the throat of a sheep). In broad terms, there is no overlapping between techniques and usages, given that the same technique (cutting) can be used for different usages (to feed, to hunt, to defend oneself) and, conversely, the same usage (to defend oneself) can be achieved by different techniques (cutting, percussion, etc.; for a discussion on this aspect, see Osiurak et al. 2008b, 2009, 2010, 2011). The distinction between technique and usage is rarely made in cognitive psychology so that functional knowledge refers sometimes to a technique (a knife is useful for cutting) and sometimes to a usage (a knife is a kitchen utensil). 4CT proposes a clear distinction by assuming that technical reasoning and semantic memory/reasoning are the bases for knowledge of techniques and usages⁷, respectively.

This assumption is consistent with the fact that neuropsychologists generally assess semantic memory by asking patients to match pictures of tools to their usual object or location (e.g., Bozeat et al. 2002; Goldenberg and Spatt 2009; Hodges et al. 1999, 2000). Knowing that the picture of a knife matches to the picture of a potato or a kitchen corresponds to knowing that knife, potatoes and all the tools and objects found in a kitchen are generally used for the same usage, that is, feeding/cooking. In fact, with regard to everyday activities, each semantic category is organized around a usual function (e.g., relaxing; sleeping), consisted of tools and objects devoted to that usual function (sofa, TV monitor and low table; bed, pyjama and pillow). 4CT assumes that this categorical organization of object-based knowledge allows people to know what can be the appropriate tools and objects for a specific usage and where to get them, thus solving the space constraint. This is consistent with the initial definition of semantic memory, namely, a system allowing us to think about things that are not here now (Tulving 1972, 1985). Given that semantic memory in 4CT is viewed as a process allowing people to solve the space constraint, the term “semantic reasoning” will be used hereafter.

5.4.2. Semantic reasoning and dialectical process

4CT posits that, like for the mechanical constraint, the space constraint is solved by a dialectical process, bringing into play the semantic reasoning and the production system. Imagine that our cook while sitting on his sofa, watching TV, intends to eat a slice of bread with jam. Nothing is present and he wants to prepare it in front of the TV set because he does not want to miss his favorite television program. For the sake of clarity, only the sub-goal “slice of bread” will be considered. The desired state (i.e., goal) is the presence of a slice of bread whereas the current state is the absence of bread. As suggested above, the problem emerges from the initial relationship between the cook and the current state. Without semantic reasoning, our cook can try to look everywhere for bread by using his production system. The first movement of the dialectical process consists in getting out of this initial relationship to access semantic knowledge. By using it, our cook can know that bread can be found in supermarkets, baker’s shops or kitchens, and more particularly, in his kitchen⁸. Even if our cook knows/remembers where to get bread, this action cannot occur without the intervention of his production system (e.g., to actually go to his kitchen). This is the second movement of the dialectical process (see above).

Imagine that our cook is a little bit distracted and notices, while coming back to his sofa, that the initial sub-goal (i.e., a slice of bread) is not reached (**Figure 5**). As explained above, he can use mechanical knowledge to determine that a cutting action can be appropriate. The invariant of the technical opposition is still the loaf of bread and the free element is something that is ABRASIVENESS+, HARDNESS+, and WIDTH- relatively to the loaf of bread (see above). Again, without semantic reasoning, our cook should have to probe the workspace or near spaces to seek an object possessing these features. In fact, this is what we do in most cases when we have no specific tool for a given everyday problem (e.g., looking everywhere in the house for something long enough to get a small ball that rolled under the sofa). However, our cook can use semantic reasoning and seek in the category

“cooking” whether there would not be something appropriate, leading him to get a knife from his kitchen.

< Insert Figure 5 about here >

5.4.3. The space constraint is not a matter of transport

Evidence indicates that people take more time to initiate grasp-to-use actions than grasp-to-transport actions (e.g., Jax and Buxbaum 2010; Valyear et al. 2011). This is consistent with the hypothesis that using a tool requires long-term tool-use representations and, as a result, implies more time to be initiated because visually available information is not sufficient for an appropriate use. By contrast, transporting an object would not require long-term representations because all the useful information is present in the visible object (e.g., Buxbaum and Kalénine 2010; Daprati and Sirigu 2006). These studies ignore that the support on which the object has to be moved – generally a table – has systematically the features (e.g., weight, solidity) suitable for being a good support, so that participants do not have to analyze the mechanical relationship between the tool or the object to be moved and the support. In this way, it can be hypothesized that initiating grasp-to-transport actions might take more time than initiating grasp-to-use actions if participants are required to move an object on a “fragile/delicate” support (for results consistent with this hypothesis, see Osiurak et al., 2013b).

The hypothesis that technical reasoning can also be involved in transport actions may appear at odds with the assumption that the space constraint is solved by semantic reasoning. However, this is not the case in that the role of semantic reasoning is not to allow mechanical transformations, including those involved in transport actions, but to help the individual to know where the relevant tools and objects can be found. Said differently, the space constraint is not a matter of transport per se, but rather of search in memory.

5.5. *THE TIME CONSTRAINT*

5.5.1. **The environmental regulation**

As discussed so far, the notions of goal and sub-goal in 4CT refer to desired states of the world. Concerning the mechanical and space constraints, the desired states of the world are the transformation of an object and the presence of a tool or an object, respectively. When engaged in an everyday activity, we progressively satisfy the sub-goals to reach the intended goal. However, we are also able to maintain a sub-goal and to perform processing (with technical and semantic reasoning) on it to generate other sub-goals. 4CT assumes that the ability to maintain goals and sub-goals in order to perform technical and semantic processing is supported by working memory⁹. A critical feature of working memory is that it enables people to perform processing on future states of the world and, as a result, not to be only subject to environmental feedbacks.

To understand the role of working memory, imagine that our cook suffers from a working memory deficit. His goal is still to eat a slice of bread with jam and he still wants to prepare it in his living room because of his favorite television program. By using semantic reasoning he can know that he can get bread from the kitchen, satisfying the sub-goal “presence of bread”. However, given that he cannot maintain this sub-goal in order to perform other processing, he is forced to get the loaf of bread. Now that the loaf of bread is present, he has no more need to maintain this sub-goal (environmental feedback). So he can now solve the mechanical constraint consisting in transforming the loaf or bread into a slice of bread. This can lead him to think about the cutting action and, by using semantic reasoning to know that he has to get a knife in his kitchen. Given that he cannot maintain other sub-goals, he has to go to his kitchen to get the knife, and so on. In sum, our cook cannot do otherwise than progressing step by step through the activity by using environmental feedbacks to compensate

his working memory deficit, at the risk of making several round trips between the kitchen and the living room (**Figure 6**).

< Insert Figure 6 about here >

5.5.2. Working memory

As suggested above, working memory allows to maintain sub-goals and to perform processing on them, generating other sub-goals to maintain, and so on. Consider now that our cook possesses a working memory (**Figure 7**). Without standing up from the sofa, he can use semantic knowledge and determine that both bread and jam can be brought back from the kitchen (two sub-goals). His working memory can also help him to anticipate that the loaf of bread and jam cannot interact to offer the desired slice of bread with jam. To solve these mechanical constraints, he can do technical reasoning and envisage cutting and spreading actions. And, by using semantic reasoning he can envisage to do so with a knife and a spoon from his kitchen, leading to two new sub-goals: The bread is sliced and the jam is spread. However, given the current state of the world is the absence of both the knife and the spoon, he has two new sub-goals which are the presence of the knife and the presence of the spoon. In total, without performing any movement, our cook has generated a certain number of sub-goals and solutions to reach them. Note also that by maintaining all the sub-goals, the cook can decide, for instance, to bring back all the needed tools and objects together.

< Insert Figure 7 about here >

The hierarchical approach on which the dual-systems theory rests (see also Duncan 1986; Humphreys and Forde 1998) is based on the assumption that behavioral hierarchy is mirrored in the structure of the processing system, notably with the notion of schema. 4CT does not integrate this component (see also Botvinick and Plaut 2004; Rumelhart et al. 1986). Instead, it assumes that behavioral hierarchy is generated by recurrent technical and semantic processing on sub-goals, maintained in working memory.

5.5.3. The environmental regulation, again

As mentioned above, without working memory, people should guide their behavior only on the basis of environmental feedbacks. However, these feedbacks can also be used to decrease the load of working memory. Thus, if our cook brings back all the needed tools and objects together from the kitchen to his living room, their presence can suppress from working memory several sub-goals and, as a result, reduce the demand on it. Interestingly, this can also enable him if he stops the activity by watching his favorite television program for several minutes to start again the process with fewer constraints. The assumption that environmental feedbacks can serve as a form of external memory is not specific to 4CT and is also made by models from the hierarchical (Cooper and Shallice 2000) or non-hierarchical approach (Agre 1988; Botvinick and Plaut 2004; Rumelhart et al. 1986). By external memory, I do not mean that the environment maintains sub-goals in memory but rather that the progressive satisfaction of sub-goals via environmental changes reduces the need of the user for maintaining them in working memory. In a way, this is consistent with Schwartz et al. (1991, p. 408): “It is appropriate to say that the action plan is elaborated *through* action, rather than prior to action”. However, contrary to Schwartz et al. (1991), 4CT does not consider that the elaboration of the action plan is based on the activation of sensorimotor tool representations under the control of SAS, but rather that the action plan is generated through technical reasoning and semantic reasoning.

It is noteworthy that our environment (e.g., home) is organized around specific activities, certainly mirroring the semantic categories. This provides the benefit of reducing many space constraints and, therefore, the load of working memory in everyday activities. This architectural organization may have led some authors to think that many everyday activities are routine (e.g., Cooper 2002; see above). However, when we are cooking, for instance, all the needed tools and objects are not necessarily within the workspace and needs

to get them in cupboards or even in other rooms. In addition, we have to anticipate one or several mechanical transformations, also loading working memory. In other words, in these situations too, working memory is required, even if the demands on it can be progressively reduced with the progression of the activity via environmental feedbacks. This prediction can be easily tested by combining a dual-task paradigm with an everyday activity. The prediction is as follows: The more the activity progresses, the less working memory is required.

Interestingly, this prediction is not formulated by the dual-systems theory. In this theory, working memory/executive control is not supposed to be differentially taxed during the activity, given that routine activities can be made without its involvement. Testing this prediction might be an interesting way to confront the dual-systems theory with 4CT.

5.6. THE EFFORT CONSTRAINT

5.6.1. The economy of action account

Effort can be defined as the amount of energy put into a behavior. As Proffitt (2006, p. 111) stressed, “a principal law of survival is that energy consumption must exceed energy expenditure. This law implies an economy of action in which energy must be conserved; over time, expenditure must not exceed consumption”. In this frame, perception can be thought to inform people about the opportunities for action and their associated costs. More particularly, perception is not only influenced by optical and ocular-motor information, but also by purposes and physiological states. This is the economy of action account. Experimental evidence supports this view (for review see Proffitt 2006; Witt 2011a). For instance, the apparent incline of a hill can increase when people are physically fatigued, in declining health or encumbered by wearing a heavy backpack (Bhalla and Proffitt 1999; Proffitt et al. 2003). People also perceive the straight-line distance to an object as longer when they intended to grasp it by reaching around a wide transparent barrier than narrower ones (Morgado et al. 2013).

More relevant to our concerns is research indicating that the intention to use a tool also affects visual perception of distances. In their seminal work, Witt et al. (2005, Experiments 1 and 2) asked participants to estimate the distance and reach with the hand to targets that were beyond arm's reach (Hand condition). However, during half the trials, participants had to hold and reach a baton so that targets were within reach when the baton was held (Tool condition). Results revealed that participants perceived the targets as closer in the Tool condition than in the Hand condition. This difference was not observed when people were asked to hold the baton but not to reach targets at all (Experiment 3). In other words, the effect was absent when the baton was irrelevant to the task. These findings have been replicated in different situations, either by using indirect measures or by asking participants to simulate or anticipate the use of the baton (Witt 2011b; Witt and Proffitt 2008; see also Osiurak et al. 2012b).

5.6.2. Motor simulation

Motor simulation can be defined as the imagining of an action, either covertly or explicitly, without necessarily executing the action (Jeannerod 2001; see also Wolpert et al. 1995). People perform motor simulation to make judgments about the ease of an action (e.g., Decety et al. 1989). As discussed above, some studies have shown that perception can be influenced by tool use, even when people have just to imagine or anticipate the use of the tool (Witt and Proffitt 2008). To account for these findings, Witt and Proffitt (2008, p. 1489) suggested that: “simulation is useful for determining and planning the next action and promotes a sort of exploration that entails minimal costs and minimal risks. Little energy is wasted simulating various options compared with the energetic costs of trying all possible actions before deciding which was best”. In a way, the proposal is that motor simulation might be the basis for making decision with regard to our activities. The present theory is consistent with this proposal.

5.6.3. Simulation-based decision-making

4CT assumes that each time an everyday activity is performed, people simulate each of the actions in order to assess the physical or time-based effort. Said differently, motor simulation is the basis for decision-making (for similar proposals, see Solway and Botvinick 2012; Tolman 1949). Moreover, this simulation corresponds to the covert stage of the processing supported by the production system (Jeannerod 2001; Wolpert et al. 1995). Imagine our cook sitting on his sofa with only the loaf of bread present. Our cook can perform motor simulation to determine the cost that this action induces for his production system. So this can lead him to engage in a dialectical process involving both technical and semantic reasoning, producing the solution “getting a knife from the kitchen and using it”. At this step, the decision is made on the basis of the less costly option (using the hand or the knife). Moreover, according to the geographical position of our cook (sitting on the sofa, sitting on a chair of the kitchen), one option can be preferred over another.

Interestingly, this motor simulation can occur not only for mechanical transformations but also for space solutions. Imagine our cook decides to get all the needed tools and objects together from the kitchen (**Figure 8**). By performing motor simulation, he can imagine that it may be costly to get everything in one round trip, and may require him to make several round trips. So again, this can lead him to use technical and semantic reasoning to envisage the use of a tray. In sum, the decision made on the basis of motor simulation can constantly modify the course of the activity, stressing that behavioral hierarchy is flexible and constantly generated, and not constrained by a priori schema knowledge. In this way, 4CT diverges from the dual-systems theory or other models of everyday activities, which generally focus on how hierarchical behavior can be supported by cognitive processes while ignoring the involvement of effort¹⁰.

< Insert Figure 8 about here >

5.6.4. Effort assessment

At this point, two questions arise: How is the user to define what is costly? And, how the user decides? 4CT does not offer firm answers to these questions, but some hypotheses can be formulated. Biomechanical constraints have been shown to guide the selection of the posture to be performed to transport objects from one location to another (e.g., end-state comfort, Rosenbaum et al. 1990). Recently, Rosenbaum (2008) asked participants to walk along a table, pick up a relatively heavy object standing on the table and carry it to another table (i.e., target table). On each trial, the position of the object on the table varied (left side, middle, or right side) as well as the walking distance to the target table. Participants had to choose along which side of the table they preferred to walk. Results indicated that the cost of reaching distance was approximately twice the cost of the walking distance. Taken together, these findings suggest that the effort estimation might be based on a set of biomechanical constraints, including the different effectors. One possibility is that the same process occurs when people have to choose the less costly option, in situations where all the tools and objects required are present.

The issue becomes more complicated in situations where all the tools and objects are not present, generating the necessity of getting them from other spaces that are not directly visible (i.e., space constraint). For instance, this can lead the cook to estimate the effort associated with getting a knife from the kitchen and to compare it with the option of detaching pieces of bread by hand. And, what about if the cook imagines going outside to the supermarket to buy a knife, an option requiring an important series of actions (wearing the shoes, turning the door handle, going down the stairs, and so on)? Given that in such cases effort estimation cannot be accurate, one possibility is that the estimation as well as the decision is mainly made on the basis of heuristics such as, for example, the number of different actions identified (e.g., wearing, turning) or the nature of the effectors involved¹¹. An interesting avenue for future research might be to identify these heuristics. The corollary

is that, in some cases, the decision made by people might be erroneous, such as choosing an option that is not the least costly. This issue will be discussed further below.

6. EMPIRICAL EVIDENCE

6.1. FAMILIAR AND NOVEL TOOL USE

The dual-systems theory posits that SAS is involved in the control of novel tool use situations. By focusing on familiar tool use, cognitive models of apraxia are generally silent on this issue or propose the additional involvement of motor imagery (e.g., Buxbaum 2001). These proposals do not predict a strong link between novel and familiar tool use. Unlike these models, 4CT assumes that (1) technical reasoning is central to both novel and familiar tool use and (2) technical reasoning, semantic reasoning and working memory are devoted to different functions. Three lines of evidence provide support for 4CT's predictions. First, in LBD patients, real, conventional use of familiar tools (screwing a screw with a screwdriver) is strongly correlated to real, non-conventional use of familiar tools (screwing a screw with a knife) and mechanical problem solving skills (Goldenberg and Hagmann 1998; Goldenberg and Spatt 2009; Hartmann et al. 2005; Jarry et al. 2013; Osiurak et al. 2009, 2013a). Second, semantic memory can be disrupted independently from real, familiar tool use (see above) and mechanical problem solving skills (Goldenberg and Spatt 2009; Hodges et al. 1999, 2000; Jarry et al. 2013; Spatt et al. 2002). Third, mechanical problem solving skills are impaired after left inferior parietal lobe lesions but not after frontal lobe lesions (Goldenberg and Hagmann 1998; Goldenberg and Spatt 2009) and are not correlated with performance on "executive" tasks (e.g., Tower of London; Hartmann et al. 2005; Jarry et al. 2013). Finally, patients with dysexecutive syndrome perform relatively well on mechanical problem-solving tasks as compared with healthy subjects (Goldenberg et al. 2007).

6.2. SEMANTIC MEMORY AND SINGLE TOOL USE

The improvement of performance between pantomime/single tool use and real tool use is commonly interpreted by the presence of additional cues facilitating the access to semantic knowledge (see above). Evidence indicating that semantic memory and real tool use can be impaired independently questions this interpretation. 4CT proposes an alternative explanation. When people are presented with a tool in isolation, they have to form a representation of the experimenter's expectations. Even if the organization of semantic memory is necessarily based on personal experience, it is also a vehicle for social knowledge given that our everyday activities are culturally shared. Therefore, people can access information from semantic memory to represent the experimenter's expectations and thus determine the category to which the tool belongs as well as a possible usage and an object with which it can be used. Then, technical reasoning can be performed to represent the mechanical transformations, guiding the execution per se. In this frame, 4CT predicts that patients with a selective semantic impairment should be unable to demonstrate the conventional use of familiar tools presented in isolation, leading them to perform technical reasoning in order to infer potential uses from the surrounding objects. Nevertheless, performance should be improved by the presence of the corresponding object because technical reasoning enables to infer a potential use. In the latter case, this does not imply that patients access knowledge about usual function but rather that the context allows them to fulfill the experimenter's expectations¹².

Experimental evidence has confirmed this prediction. We recently described the behavior of a patient (MJC) with left temporal lobe lesions and bilateral frontal lobe lesions following a closed-head injury (Osiurak et al. 2008b). She had a severe semantic impairment and met difficulties in single tool use tasks. MJC used almost systematically the desk to show how to use the tools. For example, she used a screwdriver as a kind of gimlet, saying: "One can make a hole with it". The performance was normal when both the tool and its

corresponding object were present (real tool use) as well as when asked to show how to use familiar tools in a non-conventional way. Other studies conducted in patients with a selective semantic impairment have corroborated this report by demonstrating a close relationship between semantic memory and single tool use as well as intact ability to use novel tools (e.g., Hodges et al. 2000; Silveri and Ciccarelli 2009; Sirigu et al. 1991; Spatt et al. 2002; for a review, see Osiurak et al. 2011).

6.3. ACTION DISORGANIZATION SYNDROME AND WORKING MEMORY

The role of SAS and CT in everyday activities is unclear (see above). 4CT posits that in everyday activities working memory is necessary to maintain goals and sub-goals generated by technical and semantic processing. So patients with working memory deficits should encounter difficulties only when the number of steps becomes relatively important so that environmental feedbacks cannot help them to carry out the activity in a coherent way. Difficulties should also occur when goals and sub-goals of two concomitant activities have to be maintained.

The role of SAS has been debated on the grounds that patients with closed-head injury known to induce dysexecutive impairments show the same pattern of errors than left and right brain-damaged patients in everyday activities (e.g., Buxbaum et al. 1998). In addition, patients with closed-head injury are impaired not only when asked to perform concomitant but also single activities with or without distractors (Schwartz et al. 1998). These findings have been interpreted as evidence for nonspecific resource limitations (Buxbaum et al. 1998; see also Schwartz 1995). However, these studies suffer from a methodological problem in that patients with closed-head injury could have both executive and non-executive deficits.

In this respect, the study of Goldenberg et al. (2007) gives a clear understanding of the difficulties met by patients with dysexecutive syndrome from prefrontal lobe damage. In a first study, they asked 10 patients to perform the Tower of London, mechanical problem

solving and two everyday activities (e.g., preparing instant coffee). Results indicated that patients' performance was worse than healthy subjects for the Tower of London but not for the other tasks. In a second study, they asked 10 new patients to perform the Tower of London as well as concomitant everyday activities, such as preparing both a lunchbox and a schoolbag. They found that patients were impaired on these tasks as compared to healthy subjects. On the basis of these findings, Goldenberg et al. (2007) suggested that maintenance of goals and constraints in working memory is the crucial factor for difficulties of patients with dysexecutive syndrome after prefrontal lobe damage. This interpretation is consistent with 4CT's predictions.

7. RELATED ISSUES

7.1. THE ISSUE OF AUTOMATICITY

As the dual-systems theory, cognitive models of apraxia propose that knowledge about tool action can be *directly* activated (i.e., without any intention of use) from the mere observation of a tool. The orientation effect and utilization behavior are generally interpreted as evidence for this proposal.

7.1.1. The orientation effect

In their seminal work, Tucker and Ellis (1998) asked participants to make pushbutton responses with the left or right hand depending on whether the presented handle-tool was upright or inverted. They observed that faster right-hand responses were performed when the tool's handle was oriented to the right than to the left, and vice versa for left-hand responses (the orientation effect). Given that the orientation of the tool's handle was irrelevant to the responses, these findings were interpreted as indicating that seen tools automatically potentiate components of the actions they afford (see also Barsalou 2008; Thill et al. 2013). Other data question this interpretation.

Sensorimotor representations are supposed to be derived from past experience and, consequently, effector-specific – and even modality-specific (i.e., proprioceptive information)¹³. So, the orientation effect should not occur with foot-press responses when stimuli are handled tools. At least two studies have observed that this effect can be found when participants are asked to respond by pressing footswitches (Phillips and Ward 2002; Symes et al. 2005). To resolve the discrepancy, Symes et al. (2005) suggested the existence of an abstract motor code, weakening the initial interpretation in terms of effector-specific representations. This effect has also been found with non-manipulable stimuli, supporting an attention-directing account (Andersen et al. 2002; see also Cho and Proctor 2010).

Also tricky is the question of intentionality. Consistent with Tucker and Ellis (1998), Tipper et al. (2006) observed a similar orientation effect by using door handles as stimuli. This effect only occurred when door handles were presented in an active state (i.e., in a 5 or 7 o'clock position) but not in a passive state (i.e., in a 3 or 9 o'clock position). The active versus passive distinction is surprising because it suggests that the active nature of a tool is not determined by the user but by the tool itself. Moreover, the question is why Tucker and Ellis (1998) found the effect with tools presented in a rather passive way. The difference found by Tipper et al. (2006) between active and passive door handles might be explained by the fact that participants were presented with short video clips of a hand reaching toward, grasping, and pushing a handle down, prior to starting the experiment. This experimental manipulation might have created an intentional bias, orienting the participants to the use of door handles. Likewise, in Tucker and Ellis' study (1998) participants were told that, for some tools, upside down or upright was defined with regard to the tool's normal use. In sum, the question is whether the orientation effect observed in these studies demonstrates that *effector-specific* representations can be activated *without any intention of use* (for further discussion on this aspect, see also Bub and Masson 2010; Cho and Proctor 2010). Finally, even if we disregard

the methodological limitations, these studies might demonstrate “nothing more than embryonic reaching and grasping movements towards graspable stimuli [and] it remains to be determined that an armchair automatically affords sitting and a banana automatically affords peeling” (Vingerhoets et al. 2009, p. 488).

7.1.2. Utilization behavior

The term utilization behavior refers to the automatic elicitation of inappropriate motor response to environmental cues and objects (Besnard et al. 2009, 2010, 2011; Lhermitte 1983; Lhermitte et al. 1986; Shallice et al. 1989). For example, patients with utilization behavior can grasp and show how to use a tool, while not instructed to do so. This behavior has been associated with frontal lobe lesions, and particularly with the medial and orbital prefrontal cortex. One account of utilization behavior is that, “in the absence of a working supervisory system in the frontal lobes, perceptual input alone can lead to activation of an action schema and to its selection in contention scheduling” (Shallice et al. 1989; p. 1596; see also Blakemore et al. 2002; Cooper and Shallice 2000). The dysexecutive hypothesis is however subject to three limitations.

First, the dysexecutive hypothesis in its strong form suggests that all the patients should show utilization behavior. However, this behavior is relatively infrequent (Brazzelli et al. 1994; De Renzi et al. 1996), contrasting with the prevalence of dysexecutive syndrome after frontal lobe lesions. Moreover, recent evidence has indicated no significant correlations between utilization behavior and dysexecutive syndrome (Besnard et al. 2009, 2010, 2011). Second, instances of utilization behavior generally correspond to “toying” (a single action wherein a tool or an object is simply manipulated), and rarely to “coherent activity” (an action involving tool use; Besnard et al. 2010). Third, utilization behavior only occurs in a social context and, more particularly, during the clinical examination. After all, in its strong form the dysexecutive hypothesis assumes that we should observe some patients spending minutes to

hours to open or close the doors of the services of neurology because the handles activate the action schema “opening/closing”. The fact that the social context is particularly determinant suggests that this behavior might be due to a misunderstanding of the experimenter’s expectations (Besnard et al. 2011; Lhermitte et al. 1986). Further research is nevertheless needed to examine the validity of this hypothesis. Regardless, these findings question the idea that this behavior provides evidence for a direct-activation-of-tool-representations account.

7.2. THE ISSUE OF SIMULATION

The sensorimotor knowledge hypothesis has recently found resonance with the widespread embodied cognition approach (see Binkofski and Buxbaum 2013; Buxbaum et al. 2005; Buxbaum and Kalénine 2010). There are several versions of embodied cognition, but most of them focus on the role of simulation. In broad terms, multimodal representations are reactivated to simulate how the brain represented action, perception, and introspection associated with this experience. This approach, in its strong form, has been suggested to explain a wide range of cognitive phenomena, from motor control and space perception to reasoning, emotion, language, memory, and social cognition (for reviews, see Barsalou 1999, 2008; Pezzulo et al. 2013; Rizzolatti and Craighero 2004). The impact of this approach has, however, been discussed on the grounds that “a wholesale acceptance of embodied accounts invites permissiveness in the kinds of data that constitute evidence in support of embodied accounts. This permissiveness is accompanied by a tendency to exaggerate the explanatory force of the observations” (Chatterjee 2010; p. 105; see also Mahon and Caramazza 2008, 2009). Moreover, by focusing on data interpreted as evidence for the embodied cognition view, some researchers might ignore that some studies have challenged the role of motor simulation in tool use (e.g., Garcea and Mahon 2012; Negri et al. 2007b; Osiurak and Badets 2014; Osiurak et al. 2012a).

Regardless, another tricky issue concerns the nature of the simulation in tool actions. In line with proponents of a strong, embodied cognition approach, three types of simulation based on sensorimotor representations can be envisaged. First, sensorimotor simulation should be performed to perceive the tool's properties, such as weight, hardness, and texture (simulation for perception). To do so, people generally used highly stereotypical movement patterns, called "exploratory procedures"¹⁴ (Klatzky and Lederman 2002; Lederman and Klatzky 1987). For instance, pressure and dynamic hefting are used for hardness and weight, respectively. Second, to know how to manipulate a tool, sensorimotor representations about tool manipulation are supposed to be simulated¹⁵ (simulation for action). Third, simulation can also be made to estimate the utility and costs of body actions in function of the current environmental constraints (simulation for decision-making). For instance, imagination durations are shorter when people imagine coloring rectangles with a thick than a thin pen (Rieger and Massen 2014; see also Macuga et al. 2012). So how can people automatically simulate simultaneously sensorimotor representations underlying perception, action, and decision-making? This should generate interference because the same modality is involved.

To resolve this issue, it can be suggested that different types of simulation are performed at different moments of the action to avoid interference (1, perception; 2, action; 3 decision-making). But if so, then this would require refinement of the interpretations made from studies on embodied cognition. More specifically, if future research is not able to demonstrate that these three types of simulation can occur independently, then the more parsimonious interpretation can still be that simulation only occurs at a decision-making level, questioning the hypothesis that simulation is the support of knowledge (see Chatterjee 2010; Mahon and Caramazza 2008). This is a fundamental issue that proponents of a strong, embodied cognition approach have to resolve. 4CT is consistent with a "weak" version of this approach, by assuming that motor simulation is the basis for decision-making, by allowing

people to predict the outcomes of multiple courses of body actions and choose among them depending on their expected utility and costs. However, 4CT does not posit that simulation is the process by which people access conceptual knowledge about tool use in everyday activities.

7.3. THE ISSUE OF TOOL-USE INTERACTION

Evidence from studies in animals, neuropsychological patients, and healthy participants indicates that during tool-use interactions tools are treated as extensions of the body schema (Farnè and Làdavas 2000; Cardinali et al. 2009; Iriki et al. 1996; for review, see Maravita and Iriki 2004). There is also considerable evidence showing that during these interactions, movements are learned and planned best in terms of their perceived effects (Janczyk et al. 2012; Kunde et al. 2007; Massen and Prinz 2007; Osiurak and Badets 2014; for reviews see Massen 2013; Massen and Prinz 2009). These studies have provided support for the ideomotor principle: When people pursue a goal, the action to perform is triggered by anticipating the sensorial effects associated with the goal, which in turn activates the appropriate action (Greenwald 1970; Hommel et al. 2001; Prinz 1997). This principle has also been applied to procedural, everyday activities, such as typewriting (e.g., Rieger 2004). Procedural memory can be defined as the ability to learn and retain motor skills with repeated exposure to the same activity (Anderson et al. 2004). These findings may appear inconsistent with 4CT given that I have questioned so far the notion routine. In fact, these findings are not at odds with 4CT. More particularly, the notion of routine as suggested in the dual-systems theory implies that the behavioral organization at a conceptual level is based on a priori schemas. By contrast, the aforementioned studies indicate that during tool-use interaction (executive level), “procedural” learning skills can be used to guide the interaction. In other words, there is no contradiction between questioning the notion of routine and acknowledging that procedural learning can occur (Goldenberg 2013a).

Besides, procedural learning does not involve the understanding of the underlying mechanical transformations. After all, many people, including me, can drive a car or use a computer keyboard without understanding how the rotation of the steering wheel influences wheel direction or how the pressing of keys induces the appearance of letters on the screen. Moreover, once a technique is acquired (e.g., cutting), it can be reused during all the life, whereas without constant reinforcement procedural training is quickly forgotten (Johnson 1981). Note also that although both humans and animals are able to acquire procedural knowledge – as well as to modify their body schema during tool-use interactions (see above and Vaesen 2012) – humans alone are able to understand observable regularities of the environment in terms of unobservable causal forces (Limongelli et al. 1995; Povinelli 2000; Santos et al. 2006; Visalberghi and Limongelli 1994; Visalberghi and Trinca 1989). This distinction has also been supported by data indicating that whereas the basal ganglia, cerebellum and premotor regions are involved in procedural learning (e.g., Pascual-Leone et al. 1993), apraxia of tool use is commonly found after left inferior parietal lobe lesions and can occur in the presence of intact procedural memory (Jacobs et al. 1999). Interestingly, it has been recently shown that patients with Parkinson’s disease without dementia or severe dyexecutive syndrome perform relatively well on everyday activities, notwithstanding difficulties in the execution per se (Giovannetti et al. 2012). Yet, impaired procedural knowledge is inherent to Parkinson’s disease. To sum up, although some processes can facilitate tool-use interactions on the basis of the ideomotor principle (incorporation of the tool into body schema; procedural learning), they are not involved at the conceptual level. In this way, 4CT offers a theoretical framework to integrate the issue of tool-use interaction **(Figure 2)**.

8. ANTHROPOLOGICAL CONSIDERATIONS

Anthropologists once thought that humans were the only animals who could use and make tools. We now know this is not true. Nonhuman primates, birds, mammals, insects and several other species have been reported to show tool behavior (Beck 1980). Nevertheless, human tool use differs in at least two respects. First, while in nonhumans tool use is incidental and rare in the wild (Beck 1980; Chappell and Kacelnik 2002; van Schaik et al. 1999), we spontaneously engage in object-object manipulations and employ a wide range of tools everyday¹⁶ (spontaneity of tool use; Johnson-Frey 2007; McGrew 1992). Second, only humans are able to use a tool to create another one (use of secondary tools; Gibson 1993). 4CT offers a framework to understand these specificities.

8.1. SPONTANEITY OF TOOL USE

4CT assumes that our decisions in everyday activities are based on a motor-simulation-based process. As suggested above, an intriguing issue is whether this process enables people to systematically follow the best option. Recently, we addressed this issue by asking participants to decide between moving objects by hand (two at a time) or with a tool (four at a time; Osiurak et al. 2014). There were different quantities of objects. In addition, the tool was not within reach so they had to get it before moving the objects. We found that participants decided to use the tool even when it objectively provides less time-based benefits than using the hands.

These findings indicate that people might present the bias of overestimating the benefits provided by tool use (tool-related bias), explaining the spontaneity of tool use in humans. Three lines of research can be developed from this. First, this bias may appear inconsistent with the principle of least effort, which has been essentially supported by studies in animals (Solomon 1948). Recent evidence in humans has also confirmed this principle in situations of

cognitive effort (Botvinick and Rosen 2009; Kool et al. 2010). However, other studies in humans have challenged it in situations of physical effort, stressing that people can give priority to keeping control over minimizing effort (Osiurak et al. 2013c; Singh 1970; Tarte 1981; Waters 1937). In broad terms, the question is still to determine what are the key factors that orient decision-making in humans in tool use situations (e.g., time, physical effort, control).

Second, the tool-related bias might be due to the inability of the simulation-based decision-making process to correctly estimate the effort associated with the solutions provided to solve mechanical and space constraints. In other words, people might overestimate the benefits provided by the tool solution (mechanical constraint) and/or underestimate of the costs related to the need to get the appropriate tool (space constraint). Future research might be conducted to examine this hypothesis in more detail (see above).

Third, an interesting issue is whether the tool-related bias is not, paradoxically, more pronounced in people, who claim themselves as practical (e.g., by spontaneously using a tray to clear a table or engaging in home improvement), as compared to “non-practical” people. If so, then this is would be ironic, but relatively adaptive at the species level, in that the tool solutions offered by practical people would be more beneficial for their peers than for themselves.

8.2. USE OF SECONDARY TOOLS

The use of secondary tools is based on a dynamical, reiteration process (see Osiurak et al. 2010). This process is also present in 4CT by assuming that in everyday activities the behavioral sequence can be constantly modified by the generation of new sub-goals via the simulation-based decision-making process (**Figure 8**). This offers a potential framework to explain the use of secondary tools. For instance, instead of running to catch a small animal, a hunter can perform technical reasoning and envisage using a trap, such as a hole into which

the animal may fall. However, this solution requires digging with the hands. So, the reiteration of the process can lead him to envisage the use of a shovel to do so. This is an instance of use of secondary tools (the use of the shovel to create the hole).

9. MISCELLANEOUS

9.1. TOOL USE, HANDEDNESS AND LANGUAGE

Motor apraxia corresponds with a loss of dexterity that is more pronounced in distal rather than proximal movements. An easy way to assess it is to have patients rotate a coin with the fingers. Motor apraxia is one of the clinical signs of cortico-basal degeneration (Zadikoff and Lang 2005). This disease is characterized by an asymmetrical fronto-parietal atrophy (including the superior parietal lobes). Motor apraxia is more severe for the extremities contralateral to the more atrophied hemisphere. In other words, motor apraxia is a unilateral motor disorder.

By contrast, apraxia of tool use affects both the contra-letral and ipsilateral extremities. It is associated with left brain damage. The left hemisphere dominance for tool use coincides with left hemisphere dominance for language as well as motor control of the dominant hand in right-handed people. So an intriguing issue is whether relationships exist between the laterality of the neural substrates of apraxia of tool use and the lateralities of handedness and language. This issue was recently explored by Goldenberg (2013b) who examined 50 left-handed patients with either left or right brain damage on pantomime of tool use and real tool use. Results indicated that both pantomime of tool use and real tool use were affected similarly by left or right brain damage. This corroborates that hemispheric dominance is less lateralized and more subject to inter-individual variability in left-handed people. More importantly, these results demonstrate that the laterality of apraxia is independent from the laterality of control of the dominant hand (see also Frey 2008). Said differently, apraxia of

tool use is not a matter of motor control, as suggested by the distinction proposed here but also by other models (Roy and Square 1985) between the conceptual system and the production system.

Goldenberg (2013b) also observed a significant association between apraxia (pantomime and real tool use) and aphasia. This is consistent with a recent neuroimaging study showing in healthy participants a co-lateralization of the language and praxis networks, regardless of the participant's handedness or hemispheric dominance for language (Vingerhoets et al. 2013; see also Vingerhoets et al. 2012). In line with 4CT, these findings stress that like language tool use is based on conceptual abilities. The link between tool use and language is not new (see Frey 2008 for a recent discussion on this aspect) but the question is still to understand what is common. Goldenberg (2013b) suggested that both require access to semantic memory. 4CT provides no answer to this question. Nevertheless, by proposing a limited number of processes involved in tool use, 4CT can help future research to investigate the nature of this link.

9.2. SEX DIFFERENCES AND PERSONAL EXPERIENCE

An issue largely unexplored in the literature is whether inter-individual differences exist concerning tool-use skills. For example, there is a folk belief that men would be better tool users than women because early stone tools were supposed to be used for hunting, a male activity (e.g., Leakey 1980). Sex differences have been reported in primatology, but the results are inconsistent with this belief. More particularly, bonobo and chimpanzee females are more avid tool users, compared to males, and they use a larger diversity of tools (Boesch and Boesch 1981, 1984; Boesch-Achermann and Boesch 1993; Gruber et al. 2010; Lonsdorf 2005). Several explanations have been offered for this. In these species, mothers and daughters tend to remain close until late adolescence, enhancing social learning (Gruber et al. 2010; Lonsdorf 2005). Another possibility is that females have evolved more sophisticated

tool use skills owing to the higher nutritional demands of pregnancy and infant care (Gruber et al. 2010). Tool use activities, such as nut cracking, require controlling the strength on the nut. The excess of strength in males can lead to explosive movements and, as a result, to poor performance (Boesch and Boesch 1984). Finally, tool-use activities are solitary activities, usually out of sight of other group members. Males might favor social contact, preferring to remain with other group members (Boesch-Achermann and Boesch 1993).

In humans, one of the rare studies on this issue demonstrated that when faced with mechanical problems to be solved with novel tools, 3-year-old boys engaged more object-oriented play than 3-year-old girls and were more likely to use tools to retrieve the toy during the baseline tool-use task. However, after training, performance in both groups approached ceiling effects, suggesting that sex differences during the baseline did not reflect a difference in competency, but rather a difference in motivation to interact with objects (Gredlein and Bjorklund 2005). In neuropsychology units, it is frequent to meet clinicians wondering whether the nature of the tools employed in the tasks affects the patient's performance. This question generally arises from the fact that some tools would possess a male connotation (e.g., hammer, screwdriver) and others a female connotation (e.g., frying pan, potato masher). Unfortunately, no study so far has addressed this question, supposing that it is possible to verify that this female/male discrimination is not a mere cliché. Note that no sex difference in healthy participants has been observed in our studies (unpublished results), on tasks such as real tool use, mechanical problem solving or non-conventional use of familiar tools. Nevertheless, it is necessary to be careful with this absence of evidence, because this does not provide an evidence of absence. For example, healthy participants generally perform at ceiling levels on these tasks, possibly masking potential sex differences. In sum, an outstanding question is whether sex or even more generally personal experience can modulate tool use skills. This question must be answered if we want to be sure that the conclusions

drawn from the current neuropsychological tasks are not erroneous, because of the neglect of these factors. In this way, 4CT opens new avenues, by formulating the different processes (technical reasoning, semantic reasoning, working memory, simulation-based decision-making) that would be likely to be modulated by these factors (sex or personal experience).

10. CONCLUSION

The originality of 4CT lies in the assumption that everyday activities are multiple problem situations consisting in a definite number of constraints. Even if my proposals concerning the nature of the processes may be debatable, the strength of 4CT is to offer a coherent framework with well-defined issues, which can spur future research in neuropsychology (**Table 1**). At a theoretical level, 4CT rests upon four important hypotheses, which distinguish it from other models. First, everyday activities are not based on a priori schemas. Instead, people generate a certain number of sub-goals in order to solve several constraints. Second, each process is devoted to a specific function/constraint, and no process is multifunctional. Third, simulation is not the basis of knowledge, but only supports decision-making. Fourth, mechanical knowledge, but not manipulation knowledge, is central at the conceptual level. In this way, 4CT generates predictions that can be confronted with those of other models (**Table 2**).

< Insert Tables 1 and 2 about here >

4CT can also be regarded as a general framework aiming to overcome a certain number of epistemological beliefs. For instance, the idea that most everyday activities are routine, that is, based on automatic and/or procedural processes is deeply ingrained in the minds of psychologists and neuroscientists alike. As discussed, the question is still to know what is a routine. In addition, the assumption that tool representations can be automatically activated from the mere observation of a tool remains to be demonstrated. Note also that this

assumption is frequently associated with the notion of affordance (Borghetti and Riggio 2009; Bub and Masson 2010; Jax and Buxbaum 2010; Tucker and Ellis 1998). In this way, the hypothesis of direct activation of sensorimotor representations may be confounded with the concept of direct perception initially developed by Gibson (1979; see also Shaw 2003; Shaw et al. 1982). However, in the ecological approach to perception, the notion of directness comes from the idea that once an intention is created, all the affordances relevant to achieving this intention are perceived and can give the feeling to the individual that the environment offers him in a very direct way. This has to be distinguished from the idea that cognitive processes can be directly activated without any intention. In fact, the latter perspective might be subject to an epistemological bias, called the psychologist's fallacy by William James (1890/2007), consisting in believing that the outcome of the analysis (the feeling of directness) provides information about the analysis (the system works in a direct way; for discussion on this point and the notion of affordance, see Osiurak 2013; Osiurak et al. 2010). 4CT is in line with the ecological approach to perception by suggesting that in daily life people first generate solutions to solve problems (i.e., intentions) and then use sensorimotor transformations to interact with tools and objects.

To conclude, I would like to stress that 4CT also raises new, interesting challenges for the study of the neural bases of human tool use. As discussed above, 4CT assumes that technical reasoning, semantic reasoning and the production system would be supported by the left inferior parietal lobe, the left anterior temporal lobe and the superior parietal lobes, respectively (**Figure 9**). No specific prediction has been formulated concerning working memory, but as extensively demonstrated, the dorsolateral, prefrontal lobe appears to be a good candidate. More interestingly, the issue as to the neural bases of tool-related economy (i.e., simulation-based decision-making) remains fully open. Studies in neuroeconomics have focused so far on how people make risky decisions, in situations such as gambling. A new

challenge might be to determine whether the cognitive as well as the neural bases of gambling is the same as that for tool-related economy. A related issue is whether some neuropsychological patients present a specific deficit for assessing tool-related effort. To my opinion, these new fascinating issues might help researchers to realize that tool use is not just a matter of manipulation, but is also a matter of reasoning or decision-making.

< Insert Figure 9 about here >

FOOTNOTES

¹ Some studies have assessed the apraxic patients' ability to use several tools and objects together such as preparing instant coffee (multiple object task; e.g., De Renzi and Lucchelli 1988). These tasks are now considered as assessing the action disorganization syndrome because of the presence of several steps to achieve the goal (see below).

² The notion of "space constraint" stresses the problem that tools and objects are not always here now, that is, directly present to our senses (e.g., they are not visible because they are in another room). In this way, the emphasis is put on the problem of the absence. This differs dramatically from the perspective where the space is divided in function of the individual's capacities (e.g., reaching space). In this way, it has been shown that tool use can extend our reaching space (e.g., Farnè and Làdavas 2000; Cardinali et al. 2009; Iriki et al. 1996). Nevertheless, even if an object is out of reach, this object can still be present to the senses, if it is visible, for example.

³ Several studies have revealed serious limitations on the ability of nonhuman animals to solve tool-use situations that are relatively simple for humans (e.g., Povinelli 2000; Santos et al. 2006; Visalberghi and Limongelli 1994). In line with this, it has been suggested that tool use in animals is not based on relational representations of the underlying generative

mechanisms involved, but rather on “concrete” representations learned by trial-and-error (e.g., Penn et al. 2008). The notion of “basic processes” refers here to this kind of learning.

⁴ Interestingly, nonhuman, animal users fail transfer tasks (Martin-Ordas et al. 2008; see Penn et al. 2008). These findings provide support for the idea that humans are able to reinterpret the physical world in terms of unobservable, hypothetical entities, such as causal forces (Penn et al. 2008; see below).

⁵ The simulation-based knowledge is confronted with some limitations that will be discussed later.

⁶ The term technique is used here as synonymous with “mechanical knowledge”.

⁷ Semantic memory can be defined as “that system which processes, stores and retrieves information about the meaning of words, concepts and facts” (Warrington 1975). In other words, it allows us to think about things that are not here now (Tulving 1985).

⁸ Of course, this is not to deny that it is different to *know* that knives can generally be found in kitchens or supermarkets and to *remember* that we possess the appropriate knife in our kitchen or the supermarket where we used to go. This issue is at the heart of important controversies concerning the distinction between semantic and episodic memory introduced by Tulving (1972). Unfortunately, this issue is beyond the scope of the present article, so I will only refer to semantic knowledge to describe the ability to think about things that are not here now. Of particular interest here is that semantic knowledge is fundamental to categorize the tools and objects in function of different activities, from very basic (body self-care, feeding, sleeping) to “non-basic” activities (relaxing, playing the guitar, working). And, it is this categorical organization, which allows us to know and even to remember how to get the appropriate tools and objects. In other words, semantic memory is viewed here as the means to organize the search in memory.

⁹This conception of working memory is quite consistent with current models (e.g., Baddeley 2003).

¹⁰Tools can also be used to enhance cognitive skills (Jonassen 1992; see also Vygotsky 1978). For instance, abacuses and pocket calculators improve calculation efficiency, and diaries and portable phones facilitate remembering the activities to perform. These tools might suggest that cognitive effort is also assessed when people are engaged in everyday activities. Unfortunately, this issue is beyond the scope of the present article.

¹¹The simulation-based decision-making process has to be viewed as a dynamic process in that the effort associated with each option can be re-evaluated all along the activity. For instance, a user can choose to reach a ball that rolled under a sofa with the arm and then decide to get an umbrella to reach the ball with it.

¹²As stressed above, a potential mistake might be to believe that when patients show how to use a tool in a conventional way, they necessarily access information about the usual function.

¹³Recent evidence demonstrates that the perception of the length of rods via dynamic touch can be recalibrated after a training session with auditive feedback (Wagman and Abney 2012). Even if these results were not obtained in a tool-use situation, they indicate that the perception of object properties is not specific to a particular perceptual modality but constrained by the object's mechanical properties.

¹⁴These procedures have been reported to be impaired in brain-damaged patients, particularly those with damage to superior parietal lobes (Binkofski et al. 2001). The term of tactile agnosia/apraxia have been proposed, stressing the importance of both the sensory and motor components of the disorder. Note also that, besides these stereotypical exploratory procedures, people can perceive a certain number of properties of objects (e.g., mass, length), without the benefit of vision, simply by wielding the objects. This kind of touch is referred to

as dynamic touch (Turvey 1996; Wagman and Abney 2012). Interestingly, it has been shown that people are able, via dynamic touch, to determine whether an object is more suited for a given tool-use action (e.g., hammering) than for another one (e.g., poking; Wagman and Carello 2001; see also Wagman and Carello 2003).

¹⁵ Proponents of a strong, embodied cognition approach assume that, as people perceive visual tool or objects, simulations of potential actions can become *automatically* active in preparation for action (e.g., Barsalou 1999; Pezzulo et al. 2011). As discussed above, this proposal is debatable.

¹⁶ All human societies develop technical equipment, which is modified and improved, a phenomenon called ratchet effect (Tomasello 1999; for further discussion on this aspect with regard to the principles of dialectic and stigmergy, see Osiurak et al. 2010).

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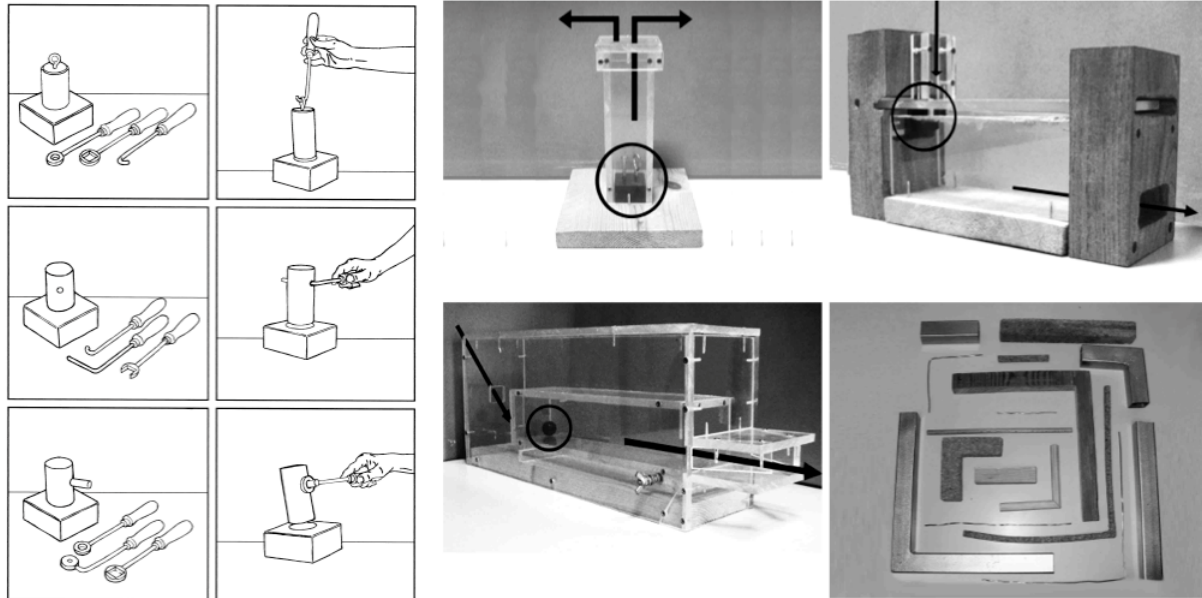
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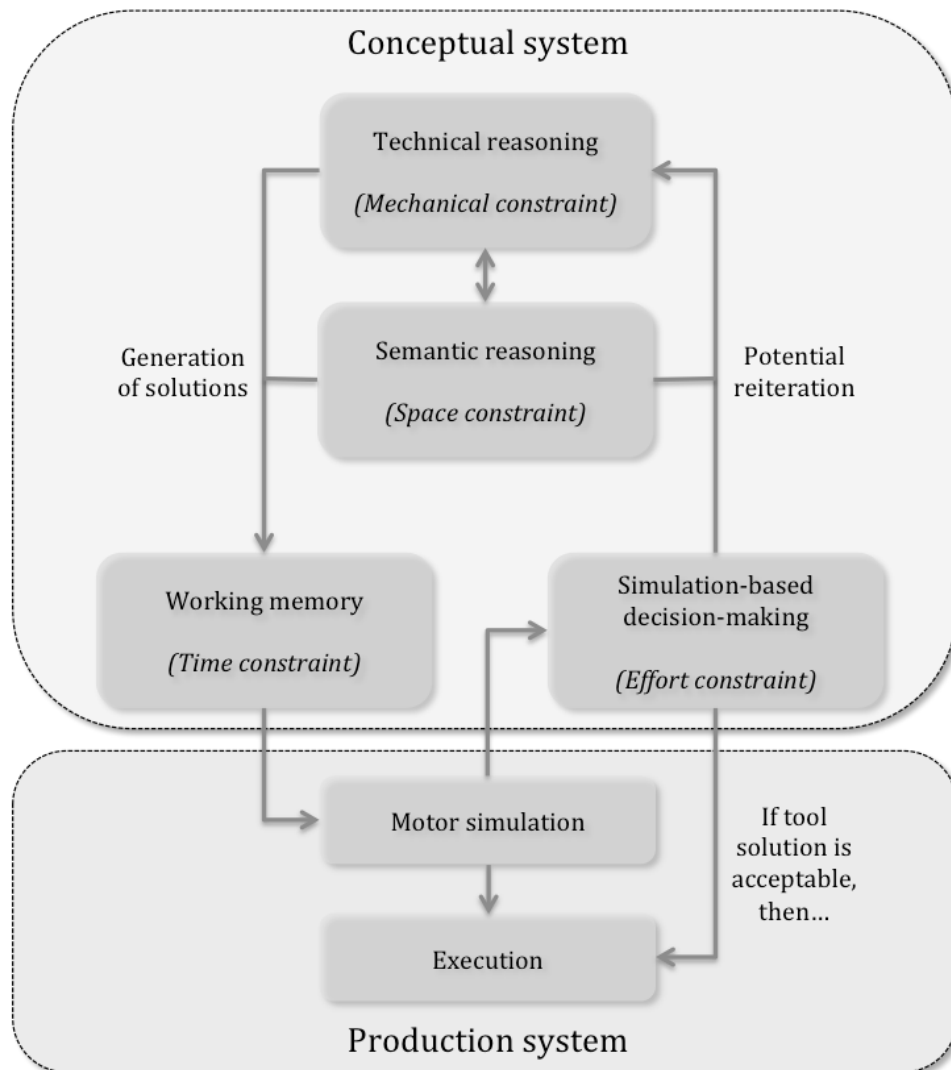
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FIGURE 1



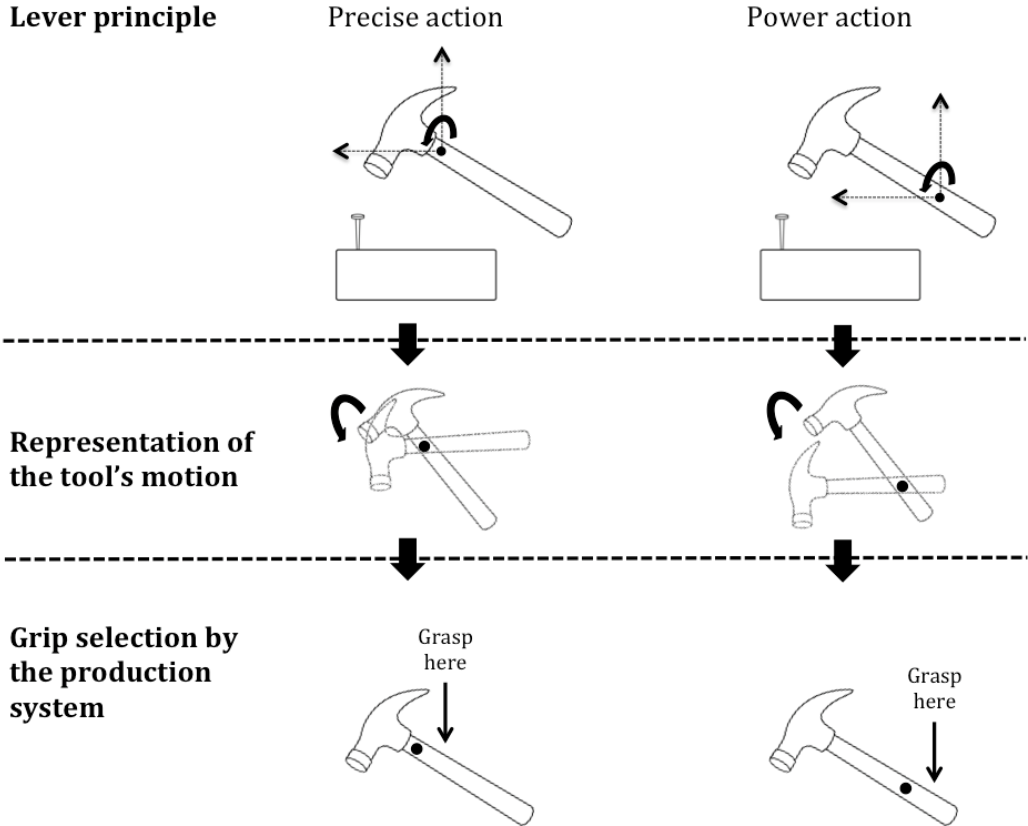
Mechanical problem solving tasks used in Goldenberg and Hagmann (1998; left) and Jarry et al. (2013, Osiurak et al. 2013a; right). In the task of Goldenberg and Hagmann, participants have to select an appropriate tool among three novel tools and to use it to lift cylinders. In the task of Jarry et al., participants have to select among 16 novel tools the one appropriate to extract a target out from a box. Reproduced with permission from Goldenberg and Hagmann (1998) and Jarry et al. (2013).

FIGURE 2



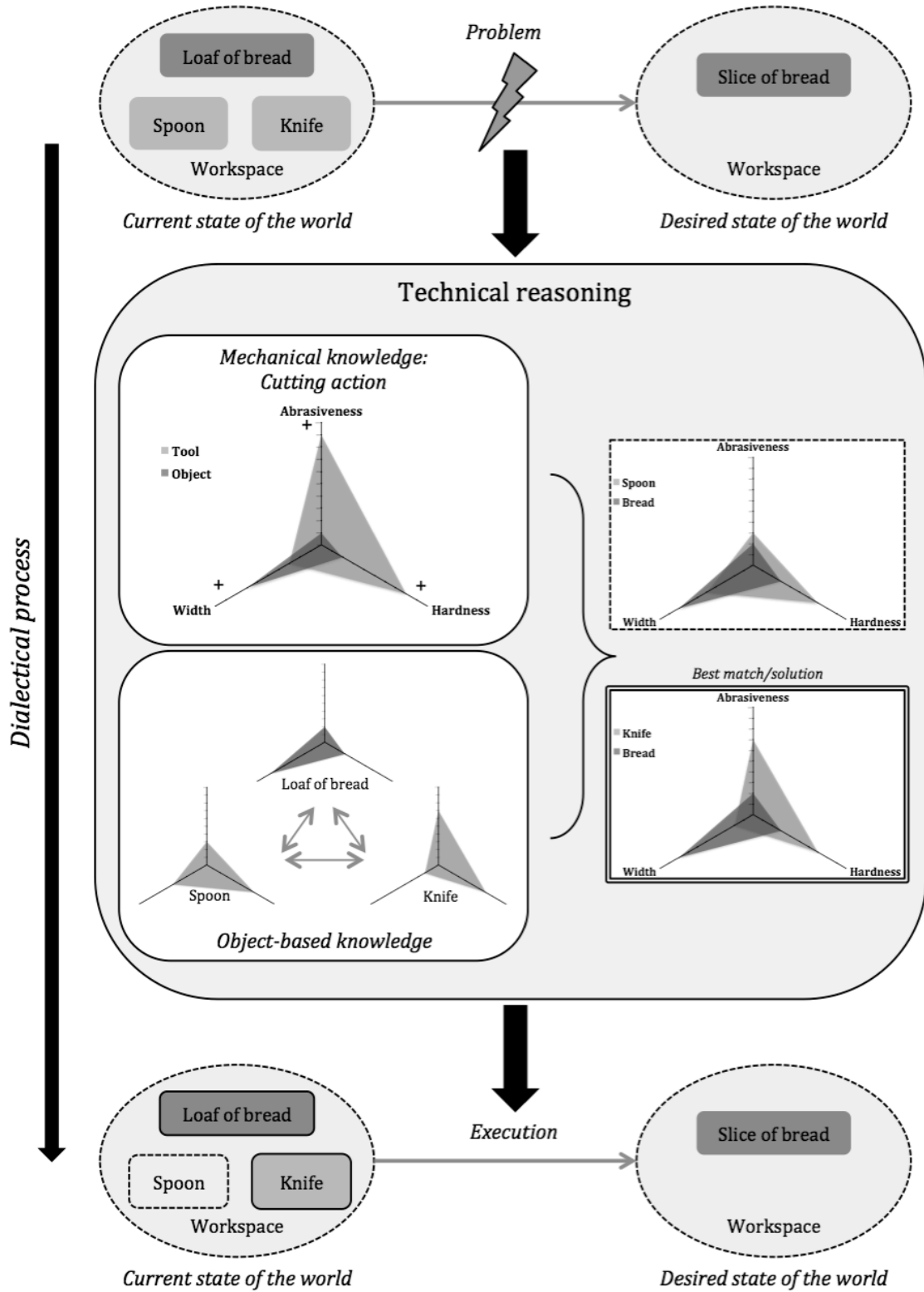
General architecture of 4CT. Explanations are given in the text.

FIGURE 3



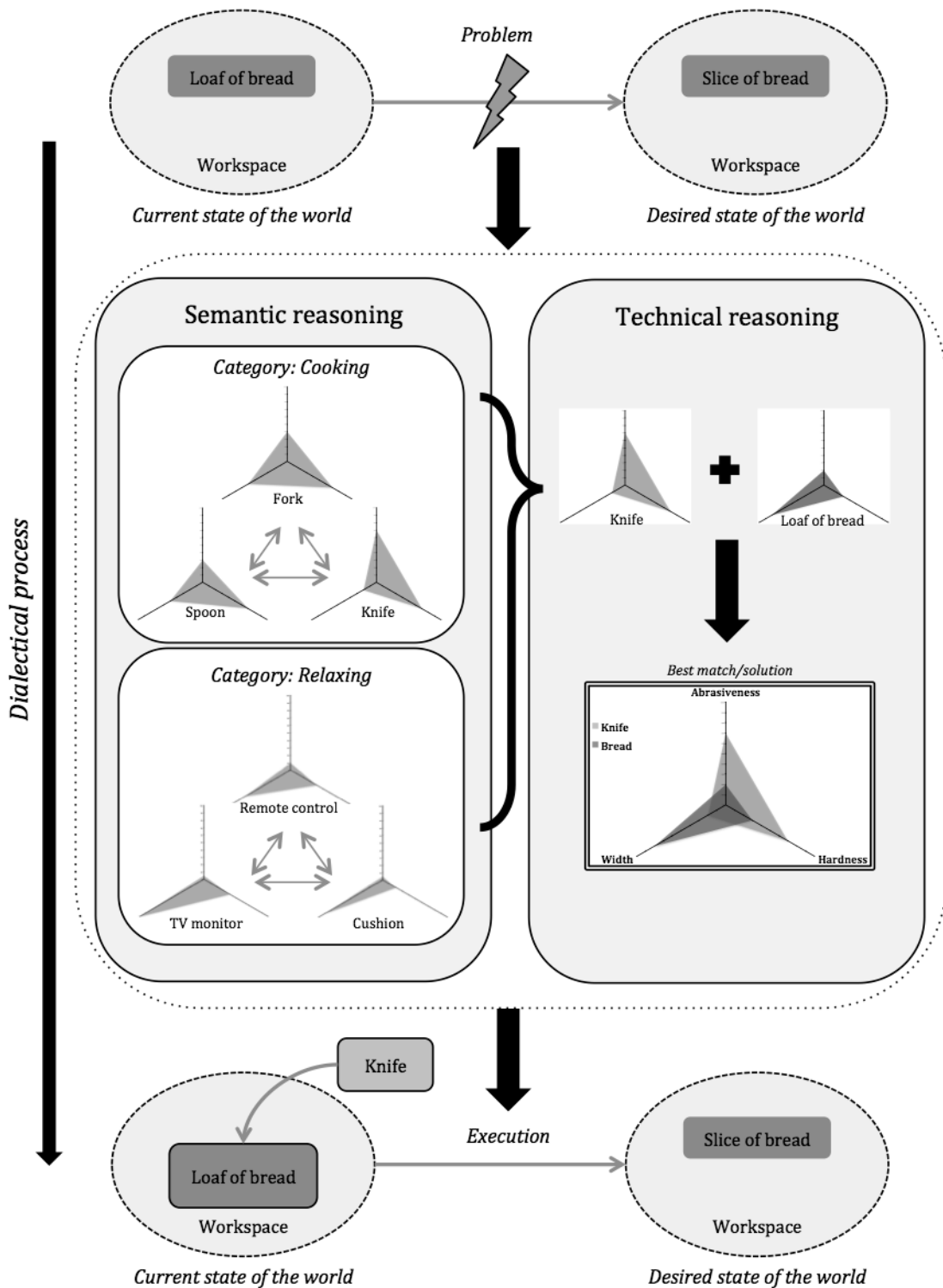
Interaction between the conceptual and the production system. Explanations are given in the text.

FIGURE 4



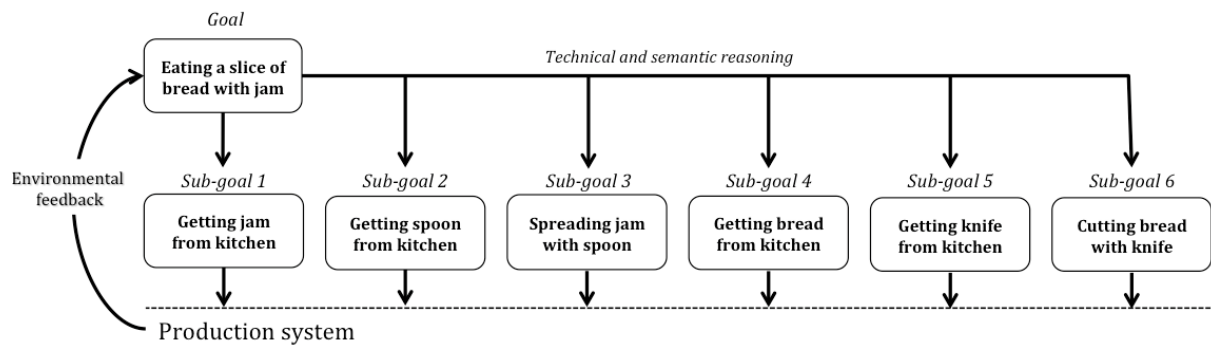
The technical reasoning process. Explanations are given in the text.

FIGURE 5



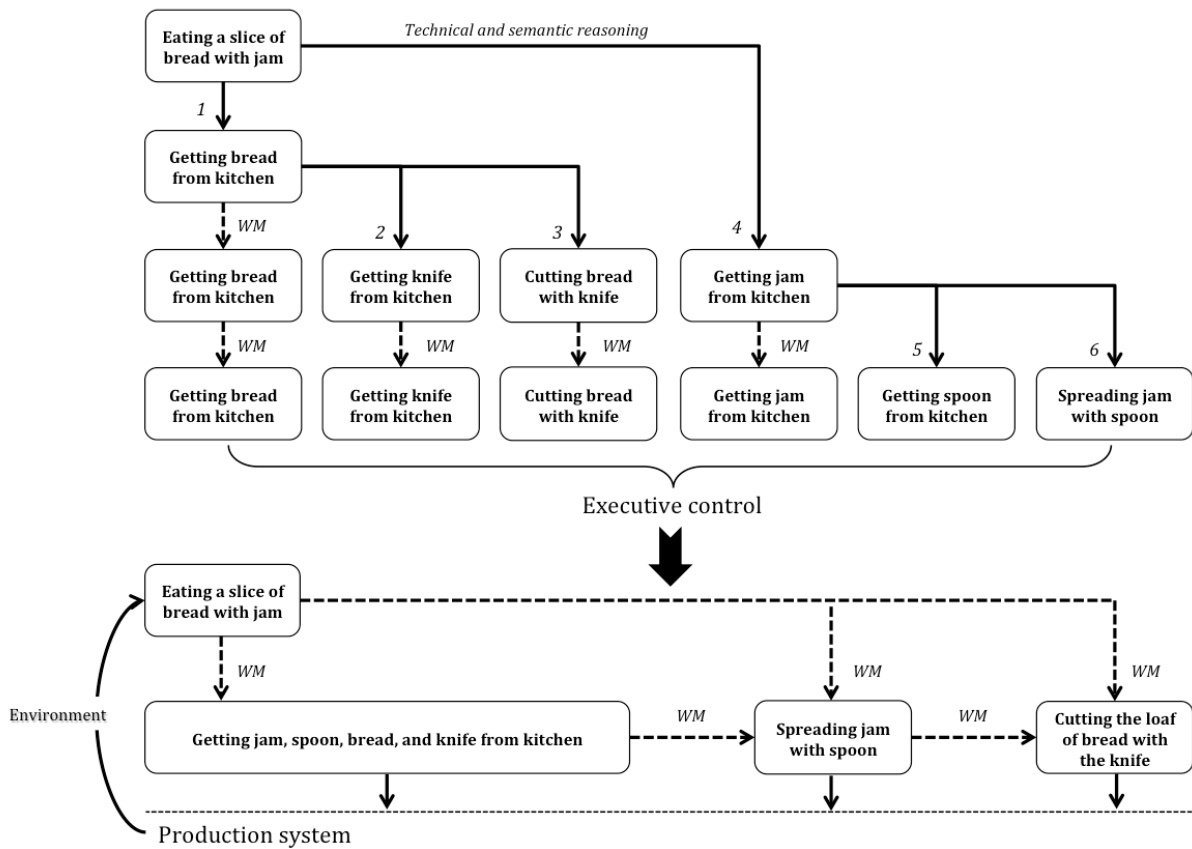
Interaction between technical reasoning and semantic reasoning. Explanations are given in the text.

FIGURE 6



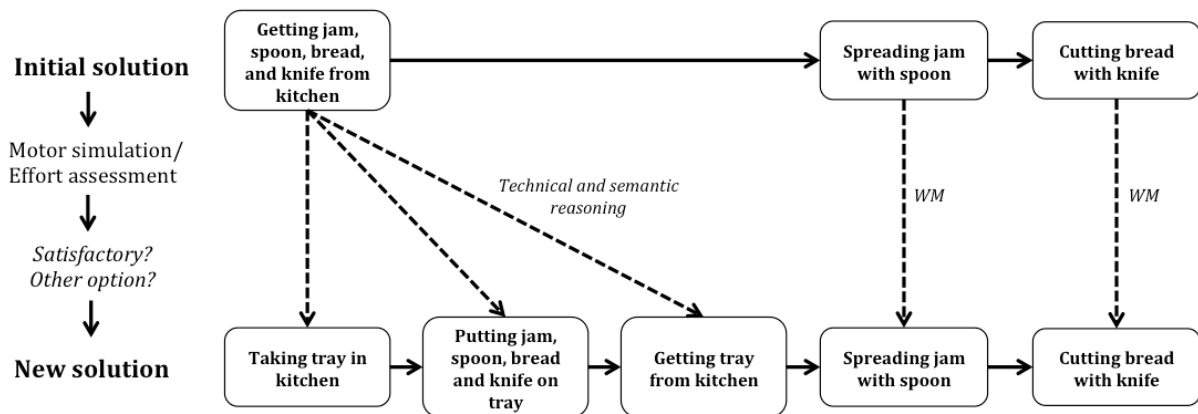
Consequences of an absence of working memory in an everyday activity. As explained in the text, each sub-goal is reached sequentially (sub-goal 1, then sub-goal 2, and so on) and the regulation of the activity is supported by environmental feedback (the presence of jam, then the presence of the spoon, and so on).

FIGURE 7



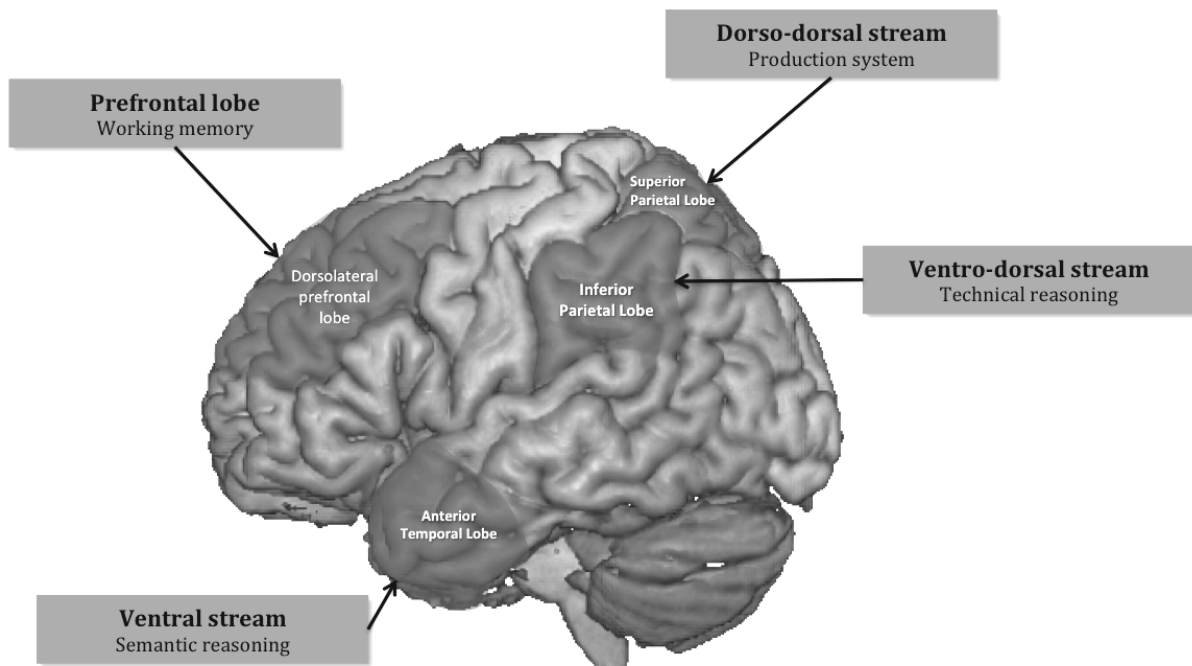
Interaction between working memory, technical reasoning and semantic reasoning. As explained in the text, all the different sub-goals of a given activity can be generated by technical and semantic reasoning and maintained in working memory (WM), even before any movement is carried out (top of the figure). Interestingly, this can lead the individual to anticipate that some of the sub-goals (getting bread from kitchen, getting knife from kitchen, and so on) can be reached simultaneously and not sequentially (bottom of the figure).

FIGURE 8



Interactions between simulation-based decision-making, working memory, technical reasoning and semantic reasoning. As explained in the text, after a solution is generated, this solution is assessed on the basis of motor simulation. This can lead to envisage another solution, on the basis of technical and semantic reasoning, which can modify the initial sequence of sub-goals.

FIGURE 9



Hypothetical neural bases of 4CT. The neural bases of tool-related economy (i.e., simulation-based decision-making) is absent from the figure, because there is no neuropsychological evidence concerning this process.

Table 1.
Syndromes, etiologies and tasks of interest

<i>Syndrome (process)</i>	<i>Etiology</i>	<i>Task of interest</i>
Apraxia of tool use (technical reasoning)	Left hemispheric stroke, Alzheimer's disease, Cortico-basal degeneration	Real tool use, mechanical problem solving
Semantic deficits (semantic reasoning)	Left hemispheric stroke, Semantic dementia	Semantic matching, single tool use
Action disorganization syndrome (working memory)	Dementia (diverse), Left and/or right hemispheric stroke, Closed-head injury	Concomitant everyday activities
"Effort-based decision-making disorders" (simulation-based decision-making)	Not yet examined in neurological patients in the context of tool use	Not yet examined in neurological patients in the context of tool use

Table 2.
Theoretical divergences between 4CT and other approaches to human tool use

<i>Cognitive models of apraxia</i>	<i>4CT</i>
Manipulation is central at the conceptual level.	Sensorimotor knowledge about tool manipulation is not present at the conceptual level.
Mechanical knowledge is not thought as an independent type of knowledge.	Mechanical knowledge is central at the conceptual level.
Knowledge about egocentric relationships (user-tool) is present at the conceptual level (sensorimotor representations).	Representations of egocentric relationships are created by the production system.
Both sensorimotor and semantic knowledge can support tool use (parallel routes for action; multifunctionality).	Technical reasoning and semantic reasoning are devoted to specific functions (orthogonal processes; unifunctionality).
The clinical conditions of evaluation (e.g., single versus real tool use) play a role by inducing more activation.	The clinical conditions of evaluation play a role because of the representations of the experimenter's expectations the participant has to form.
Tool knowledge can be activated automatically, without any intention of the user.	Tool knowledge are not activated automatically, but are recruited depending on the intention of the user.
<i>Dual-systems theory</i>	<i>4CT</i>
Everyday activities can be viewed as routine and do not require SAS.	Everyday activities are not routine and require working memory.
The organization of behavior in everyday activities is supported by schemas (hierarchical approach).	The organization of behavior is reconstructed de novo through technical and semantic reasoning (non-hierarchical approach).
SAS is involved in novel situations.	Novel tool use can be supported by non-executive processes (i.e., technical reasoning).
<i>The strong form of embodied cognition approach.</i>	<i>4CT</i>
Knowledge is based on sensorimotor simulation.	Object-based knowledge might be modality-specific but do not necessarily require sensorimotor simulation.
Several types of simulation can be performed for different functions from the mere observation of a tool (perception, action, decision-making).	Motor simulation is only involved in decision-making.