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Abstract

Various distinct cognitive processes such as semantic memory, executive planning or technical reasoning have been shown to support tool use. The aim of this study is to investigate the relationship between these processes. To do so, a large apraxia battery was submitted to 16 patients with left brain-damage (LBD) and aphasia and 19 healthy controls. The battery included: classical apraxia tests (Pantomime of Tool Use and Single Tool Use), familiar and novel tool use tests (Tool-Object Pairs and Sequential Mechanical Problem-Solving), semantic memory tests (Recognition of tool utilization gestures and Functional and Categorical Associations) as well as the Tower Of London. The Sequential Mechanical Problem-Solving task is a new task which permits the evaluation of pre-planning in unusual tool use situations. In this task as well as in the Tool-Object Pairs task, participants solved a tool use problem in a Choice and a No-Choice condition to examine the effect of tool selection. Globally, left brain damaged patients were impaired as compared to controls. We found high correlations in left brain-damaged patients between performances on classical apraxia tests, familiar and novel tool use tests and Functional and Categorical Associations but no significant association between these performances and Tower Of London or Recognition of tool utilization gestures. Furthermore, the two conditions (Choice and No-Choice) of Tool-Object Pairs and Sequential Mechanical Problem-Solving were associated. In sum, all tasks involving tool use are strongly associated in LBD patients. Moreover, the ability to solve sequential mechanical problems does not depend on executive planning. Also, tool use appears to be associated with knowledge about object function but not with knowledge about tool manipulation. Taken together, these findings indicate that technical reasoning and, to a lesser extent, semantic memory may both play an important role in tool use.

Keywords: Apraxia of tool use; Mechanical problem-solving; Semantic memory; Executive planning; Technical reasoning.

1. Introduction

First observations of tool use impairment were provided by Steinthal's (1871) study of an aphasic patient with deficits in the manipulation of everyday tools (see Goldenberg, 2003). A few decades later, Liepmann (1908, 1920) shaped the concept of apraxia, a disorder of skilled movement that cannot be attributed to an elementary sensorimotor deficit or to aphasia (De Renzi, 1989). Liepmann proposed that tool use is supported by the creation of a visual or acoustic image of the action (i.e., movement formulae) in the posterior brain regions. He proposed the term ideational apraxia to describe patients who had difficulties in generating movement formulae. Later, De Renzi and Luchelli (1988) specified that ideational apraxia could pertain "to the area of semantic memory disorders rather than to that of defective motor control" (p. 1173) and proposed the term "amnesia of usage". To date, three main classes of cognitive processes have been propose to account for tool use impairment. We propose to review these processes on the basis of three hypotheses: the semantic memory hypothesis, the executive planning hypothesis and the technical reasoning hypothesis.

First, the semantic memory hypothesis, which originates from Liepmann's and De Renzi's works, assumes that tool use is based on knowledge about (1) tool manipulation (or gesture engrams) and (2) tool function (Buxbaum, 2001; Buxbaum et al., 2003, 2007; Heilman et al., 1982; Rothi et al., 1991; Sirigu et al., 1995). Gesture engrams are "thought to contain the features of gestures which are invariant and critical for distinguishing a given gesture from others. For a hammering movement, for example, a broad oscillation from the elbow joint is critical, as is a clenched hand posture…" (Buxbaum, 2001, p. 452). Buxbaum (2001) stressed that damage to this "stored representational system of gesture" has an impact particularly on pantomime production and recognition, manipulation knowledge and tool use (mis-selection of objects, object misuse, object omissions, sequence errors). Besides gesture engrams, the human brain would also contain semantic information about the familiar function of tools (Cubelli et al., 2000; De Renzi and Lucchelli, 1988; Ochipa et al., 1994; Rothi et al., 1991; Roy and Square, 1985). This conceptual knowledge supports representation about tool associations (matching object to recipient) and about purposes of the actions (matching object for shared purposes) (Hodges et al., 2000). There are divergent views on the functional subdivisions of semantic memory but all previous research concurs in assuming that specific tools are associated with specific actions (Goldenberg and Spatt, 2009).

The semantic memory hypothesis has however been subject to criticism on theoretical as well as empirical grounds in recent years. For instance, Osiurak et al. (2011) claimed that the role of gesture engrams in tool use remains unclear, notably if it is assumed that tool use is supported by a direct route from vision to action (Humphreys, 2001; Yoon et al., 2002). More importantly, Osiurak et al. (2011) emphasized that evidence for the existence of gesture engrams is weak, if not absent. Likewise, many studies have demonstrated that semantic knowledge is neither necessary nor sufficient to support tool use (Buxbaum et al., 1997; Hodges et al., 2000; Osiurak et al., 2008; Silveri et al., 2009). It has also been suggested that semantic knowledge about tool function may be mainly involved in situations in which contextual information is lacking as would be the case, for example in situations in which a tool is presented in the absence of contextual cues (Osiurak et al., 2008). Nevertheless, even if semantic knowledge could help people to determine the usage of tools, this kind of information would not be involved in utilization *per se* (Osiurak et al., 2011). Finally, the semantic memory hypothesis cannot account for everyday use, which generally requires carrying out unusual manipulations and uses of unfamiliar tools (Goldenberg and Spatt, 2009).

Second, the executive planning hypothesis, inspired by Luria (1978) suggests that dysexecutive syndrome has a negative impact on everyday tool use. Luria (1978) proposed the term "frontal apraxia" to describe a breakdown in sequential organization of behavior.

Patients with this type of apraxia do not show classical ideational apraxia in that usual actions are performed perfectly, but disturbances arise in natural actions requiring a preformed plan and the maintenance of goals (Poeck, 1983; Schwartz et al., 1993, 1995; Goldenberg et al., 2007). Schwartz et al. (1998) suggested that this “action disorganization syndrome” is independent from “specific impairments of planning” described by Shallice (1982) because it concerns familiar activities involved in daily life. Goldenberg et al. (2007) pointed out that dysexecutive syndrome is specifically associated with multi-step actions impairment which is one symptom of “the general depletion of working memory capacity or attentionnel resources” (p. 434). Hartmann et al. (2005) showed dissociation between naturalistic multi-step actions and tests solved by pre-planning (novel tools, Tower Of London) in LBD patients. These works indicate that pre-planning would play a role in certain situations involving tool use but is probably not a unitary concept.

Finally, the technical reasoning hypothesis (Gagnepain, 1990; Le Gall, 1998; Osiurak et al., 2009, 2010; for a somewhat similar view, see Goldenberg and Hagmann, 1998; Goldenberg and Spatt, 2009) suggests that technical efficacy is always relative, not absolute, because technical reality does not correspond to physical reality (Osiurak et al., 2010). For example, the physical material “glass” can provide distinct technical properties (permeable, resistant, transparent …) but the same technical property (resistant) can be provided by a variety of different physical materials (wood, metal, plastic …). Moreover, the same physical material does not always provide the technical property suitable for an intended action. For example, the lead of a pencil is friable when applied to paper but not to leather. Thus, the inability to use tools may reflect difficulties in identifying (distinction) and unifying (sequenciation) the technical means (dense, permeable, resistant, etc.) relevant for a given technical end (cutting, engraving, etc.). Technical means and ends are abstract principles which are not linked with any tool representation but are reconstructed *de novo* depending on each situation. In case of impairment, difficulties would mostly affect technical means or technical ends. So, technical reasoning would be involved in any situation requiring the use and the selection of tools: use of familiar tools in either conventional or unusual ways as well as mechanical Problem-Solving. Furthermore, this hypothesis predicts that patients with impaired technical reasoning would exhibit difficulties with single tool use or single associations between tool and object upon which the tool is to be used and also in situations in which a great number of tools is given. Consistent with this, patients with ideational apraxia can be perplexed, commit mislocation errors or engage in uncertain explorations when asked to perform multiple object use tests (De Renzi and Lucchelli, 1988; Rushworth et al., 1998).

There is a substantial amount of empirical support for the technical reasoning hypothesis. We recently observed that LBD patients with difficulties in using familiar tools were markedly impaired when asked to use familiar tools in an unusual way (Osiurak et al., 2009). Several studies have found a strong association in LBD patients between the capacity to use familiar tools and mechanical Problem-Solving skills (Goldenberg and Hagmann, 1998; see also Goldenberg and Spatt, 2009; Hartmann et al., 2005; Silveri and Ciccarelli, 2009). Moreover, Goldenberg and Hagmann (1998) demonstrated that left brain lesions especially disrupt the capacity to select novel tools to solve mechanical problems. It has also been shown that patients with dysexecutive syndrome do not fail to perform mechanical Problem-Solving tests or to pantomime object use and that novel tool use was not affected by dysexecutive syndrome (Goldenberg et al., 2007). These findings indicate that executive functions might not be involved in situations in which people are asked to solve problems with unfamiliar tools (Goldenberg et al., 2007; Hartmann et al., 2005; Rumiati et al., 2001; Rushworth et al., 1998). Nevertheless, the mechanical problem-solving test developed by Goldenberg and Hagmann (1998) from which most of the results discussed above have been obtained, does not require a sequence of actions to solve the problem. These authors also developed the Treasure Box test, consisting of three boxes with lids that can be opened after manipulation of several locks. Premature opening of one lock could block the opening of another lock, so each stage depended on the previous one. Although these boxes required a sequence of mechanical actions to be solved, the solution could be found by trial and error. Pre-planning was not necessary, which left open the issue of this ability's involvement in mechanical problem-solving.

The present research is designed to clearly distinguish these three hypotheses. We assessed 16 patients with left brain-damage (LBD) and aphasia and 19 healthy controls with a large apraxia battery examining semantic memory, executive planning and technical reasoning. Participants were asked to perform tasks typically studied in apraxia research (Pantomime of Tool Use, Single Tool Use), semantic memory tests (Functional and Categorical Associations and Recognition of tool utilization gestures) and a multiple-step executive function test (Tower Of London; Shallice, 1982). Above all, we proposed original tests requiring the actual use of familiar tools (Tool-Object Pairs) and the use of novel tools (Sequential Mechanical Problem-Solving). Like the novel tool test developed by Goldenberg et Hagmann (1998), we proposed two conditions for both tests (Tool-Object Pairs and Sequential Mechanical Problem-Solving). In the Choice condition subjects had to select among several tools the relevant one to perform the task. In the No-Choice condition, only the relevant tool was given.

Different theoretical elements allow us to make different predictions about the expected deficits according to each hypothesis (Table 1) and about the possible interactions between tasks. The memory hypothesis assumes that people acquire knowledge about manipulation and function of tools with which they had prior experience. Thus, gesture engrams and functional knowledge should be necessary to ensure the selection and the use of familiar tools but not when people have to solve sequential mechanical problems or carry out tests requiring executive functions. So, the semantic memory hypothesis allows us to expect associations between semantic memory (Recognition of tool utilization gestures and Functionnal and Categorical Associations) and familiar tool use (Tool-Object Pairs). However, the semantic memory hypothesis does not predict any association between semantic memory and novel tool use (Sequential Mechanical Problem-Solving). Moreover, this hypothesis does not predict any association between the performance in Tool-Object Pairs and that in Sequential Mechanical Problem-Solving. The same is true of the executive planning hypothesis which is also insufficient for the prediction of any such association (Tool-Object Pairs and Sequential Mechanical Problem-Solving). In contrast, given that executive functions are supposed to enable people to deal with novelty and planning problems, the executive planning hypothesis predicts a strong association between performance in Sequential Mechanical Problem-Solving and the Tower Of London. Finally, the technical reasoning hypothesis suggests that the ability to reason about technical means and ends is involved in any situation requiring the use of tools. Therefore, there should be a strong association between the performance in Tool-Object Pairs and in Sequential Mechanical Problem-Solving. However, no association is predicted between performance in these two tests and that in the Tower Of London. Of particular interest is that only the technical reasoning hypothesis predicts association between familiar tool use (Tool-Object Pairs) and novel tool use (Sequential Mechanical Problem-Solving) independently of executive planning and semantic memory abilities.

Table 1 about here
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2. Method

2.1. Participants

Patients were admitted to the neurological department of the Angers University Hospital for a first unilateral cerebral vascular accident with hemiparesis and aphasia. Clinical CT or MRI scans were available for all patients. The quality of our patients' brain images, which were collected primarily for clinical purposes and using different scanners, did not allow us to apply modern neuroimaging analyses. The patients' brain lesions were therefore classified by an experienced neurologist (VC) according to relatively general anatomical criteria. Patients had a preliminary interview with a neuropsychologist (CJ) or speech therapists (DD) to examine language and vigilance. Linguistic capacities were tested with comprehensive and expressive exercises (e.g., naming, repetition, speech comprehension, reading or writing) depending on the individual patient's abilities. Aphasia was classified as global in 1, Broca in 5, Wernicke in 4, amnesic in 2, subcortical in 2 and non-classifiable in 2. LBD subjects were included only if their behaviour unequivocally indicated comprehension of experimental test's instructions and if hemianopia did not appear to have an impact on their visuo-explorative behaviour. Our control group was composed of nineteen volunteer participants recruited from senior citizens' community associations around Angers. Preliminary screening with the Mini Mental State Examination (Folstein, 1975) attested to their cognitive efficiency (mean score 29/30, range 26-30).

All participants were right-handed, and had no previous history of neurological or psychiatric illnesses. Informed consent was obtained from all participants or their relatives, and the study was conducted in accordance with the Declaration of Helsinki. Demographic and clinical data are displayed in Table 2. All participants used their left hand in order to prevent any effect due to motor or sensory impairment in the LBD group. There were no significant differences with respect to age and gender distribution between patients and control subjects. The mean educational level was somewhat higher for patients than for controls [$t_{(33)} = 1.8$, $p = .012$].

Table 2 about here

2.2. Pantomime of Tool Use

This test consisted of ten tools (key, corkscrew, screwdriver, match, light bulb, scissors, bread-knife, bottle-opener, hammer, pitcher, electrical plug, saw) that the examiner presented one at a time on a "vertical tool panel" (Figure 1). Participants were asked to pantomime the use of each tool. Testing was preceded by two practice items (key and corkscrew) for which a correct pantomime was demonstrated if participants did not produce it themselves (Hartmann et al., 2005). The time limit was set to 1 minute for each item. The performance was videotaped and rated on a 3-point scale (Osiurak et al., 2009). Two points were given if the expected action was directly achieved within the time limit. One point was given if the participant performed the action with errors (content or spatiotemporal). No points were given when the action was completely unrecognizable (maximum = 20 for each condition).

2.3. Single Tool Use

The same tools mentioned above were presented once again on the "vertical tool panel". Participants were required to grasp, one at time, each object and to demonstrate the movement involved in its typical use. Practice items were the same as in Pantomime of Tool Use. The procedure of data recording and analysis was the same as described in the previous paragraph (maximum = 20 for each condition).

2.4. Tool-Object Pairs

This test consists of the same 10 familiar tools and the corresponding objects upon which they can be used (padlock, bottle sealed with a cork, screw in a wooden board, candle, bulb socket, sheet of paper, piece of bread, bottle sealed with a cap, nail in a wooden board, glass, electrical socket and a piece of wood). These objects were adapted to enable a one-handed performance (Figure 1).

Participants first performed tasks in the Choice condition and then in the No-Choice condition. In the Choice condition all the tools were presented simultaneously on the "vertical tool panel". One object at time was placed on the table, between the participants and the "vertical tool panel". Participants were asked to select the tool corresponding to the object upon which it was to be used and then to demonstrate the action typically made with the tool used on the object. In the No-Choice condition only the tool associated with the object was presented on the "vertical tool panel". One object at a time was placed on the table and subjects were asked to do what is typically done with the presented tools and objects. Two tools (key and corkscrew) were used as practice items, that is, subjects were helped to select the tool as well as to carry out the correct action, if necessary. The performance was videotaped and rated on a 3-point scale (0, 1, 2; Goldenberg and Hagmann, 1998; Osiurak et al., 2009). For both conditions, two points were given if the expected action was directly achieved with the appropriate tool within the time limit. One point was given if the participant performed the action within the time limit after unsuccessful trials. No points were given when the action was not successfully achieved (maximum = 20 for each condition). The time limit was set to 1 minute for each item.

Figure 1 about here

2.5. Sequential Mechanical Problem-Solving

This test was inspired by a series of studies by Goldenberg and colleagues (Goldenberg and Hagmann, 1998; Goldenberg et al., 2007; Hartmann et al., 2005) in which the Novel Tool Test was employed to evaluate patients' ability to infer function from structure. In this test, participants are asked to select (among a collection of three novel tools) the one tool that is best suited for taking up a cylinder. Nevertheless, as mentioned above, this test consists of mechanical problems that do not require a sequence of actions to be solved. Therefore, we specifically designed the Sequential Mechanical Problem-Solving based on two major principles. The first is that a sequence of several actions is required to solve the problem. The second is that trial-and-error strategies are insufficient for successful performance.

We constructed three different transparent boxes. A little blue wooden cube or a little blue wooden bead (the targets) was stuck inside each one (Figure 2). The aim of this test was to extract the target out from the box. For each box, different actions were required to do so. The test was adapted to enable a one-handed performance. For Box A, participants had to remove the lid with their hand, and then lift the target up with a hook that they had to create by folding a metal rod. For Box B, participants had to insert an appropriate rod in the "chimney", push the target down into the box and then bring the target out from the box. For Box C, participants had to first use a rigid rod to make a lever and thus lift the mobile compartment that was located inside the box. This first action permitted to bring the target (a blue wooden bead) to the entrance of the box. Then, participants could carry out the second action of using a rod to extract the target out from the box. Problems could not be resolved by using only the hands, lucky movements, trial-and-error strategies or by choosing randomly among the rods. For each problem, one particular rod was the most effective. It was the only one presented in the No-Choice condition. Each rod involved different grips and numbers of movements but most of them proposed in the Choice condition were completely useless[1]. Thus, in the Choice condition some controls and some LBD patients did not resolve the problems with the most effective rods. Nevertheless, we accepted their performance when the target was finally extracted from the box.

For each item, participants were initially invited to observe carefully each side of the box. Then, the position of the target was ostensibly shown to subjects. A target similar to the target stuck inside the box was also presented to subjects to ascertain that they identified the target to be extracted. Participants were then asked to bring the target out from the box with the available rod(s), without lifting the boxes.

All participants performed first the Choice condition and then the No-Choice condition. In the Choice condition, the 16 rods were presented simultaneously on the table on the left of the subjects. The physical properties of the rods were manipulated so that: Half of the rods were made in metal and half of wood; half have a right angle and half do not; half were cylindrical and half "parallelipedic"; half were thick and half thin; half were long and half short; and half was rigid and half flexible. In the No-Choice condition, only the supposedly more efficient rod was given to participants to solve the problem. The time limit was 3 minutes for each box in each condition and the performance was videotaped. A 4-point scale was employed in the two conditions. Three points were given if the target was extracted within the time limit, independently of the rod that was used. Two points were given if the target was moved inside the box. One point was given if the target was touched by one of the rods. If none of these criteria were fulfilled, no points were given. The maximum score for each condition was 9.

Figure 2 about here

2.6. Tower Of London

This test was proposed to assess the ability to solve multiple step problems involving minimal mechanical constraints. It was selected to minimize the effects of language skills. The test involved two identical devices (the participant's device and the examiner's device) that consisted of three sticks and three wooden beads. The examiner presented a specific configuration of beads and asked the participant to replicate the configuration on his own device. We employed a revised version of the classical Tower Of London (Berg and Byrd, 2002; Shallice, 1982). There were two examples and six problems with a range from 2 to 7 moves. Examples were used to ascertain that participants understood the rules: only one bead can be moved at time, by using only one hand; one bead could be placed on the smallest stick, and only two on the middle stick; a bead cannot be moved if the two others were not placed on the sticks. The time limit for each item was 2 minutes. Performance was rated on a 4-point scale according to the number of movements (see Table 3). The maximum score was 18.

Table 3 about here

2.7. Semantic knowledge of manipulation and tool function

Two tests were proposed to assess semantic memory. The first explored manner-of-use knowledge. The second explored functional and associative object knowledge.

2.7.1. Recognition of tool utilization gestures

This test consisted of twelve sets of four photographs. In each set, one photograph depicted the correct use of the tool, whereas the remaining three photographs showed the tool incorrectly oriented, inappropriately held or dangerously held. The tools shown on the photographs were the same that had already been pantomimed and demonstrated. Testing was preceded by two practice items for which feedback on correctness was given. One point was credited for each correct response given in 30 sec, totalling 10 points.

2.7.2. Functional and Categorical Associations

Four images with different single objects were presented below the picture of a tool (target stimulus: key, corkscrew, screwdriver, match, light bulb, scissors, bread-knife, bottle opener, hammer, pitcher, electrical plug, saw). Subjects were asked to select one out of four objects that best matched the target stimulus. Two subtests were assigned in order to evaluate either "functional" or "categorical" associations (Goldenberg and Spatt, 2009). In the subtest "functional associations", the target stimulus (e.g. saw) and the correct response (e.g. piece of wood) were functionally associated. In the subtest, “categorical associations”, the target and the correct response (e.g., a saw, an axe) could be used for the same purpose. Each subtest was preceded by two practice trials (key and corkscrew) for which feedback on correctness was given. A score of 1 point was given if the correct response was given in 30 sec, totalling a score of 20 possible points for both conditions.

2.8. Statistics

Because of unequal group sizes and partly unequal variances, non-parametric tests were preferred. Between-group comparisons were performed with the Mann-Whitney U-test. Wilcoxon signed-rank tests were used for within-group comparisons and Spearman rank order correlations were used to study relationships between variables. To further explore the correlational structure of test results in LBD patients, the correlation matrix of all experimental tests was subjected to multidimensional scaling using the ALSCAL procedure. We also carried out stepwise regression analyses to determine contribution of semantic memory and technical reasoning in familiar object use. Results were considered significant at a α-level of $p < .05$.

3. Results

3.1. Effects of demographics variables in the control group and the patient group

In the control group, Spearman rank order correlations revealed negative correlations between age and performances on Tool-Object Pairs (Choice condition, $rho = -.67$, $p = .002$; No-Choice condition, $rho = -.58$, $p = .009$) and Recognition of tool utilization gestures ($rho = -.50$, $p = .029$). Associations were also found between education level and the No-Choice condition of Tool-Object Pairs ($rho = .54$, $p = .017$) and Recognition of tool utilization gestures (*rho* = .56, p = .013). Correlations between demographic participant variables and Sequential Mechanical Problem-Solving, Pantomime of Tool Use, Single Tool Use and Tower Of London did not reach statistical significance. No significant correlations were found between global cognitive efficiency (MMSE) and any of the experimental tasks.

In LBD patients, no significant correlations were found between demographics and any of the experimental tasks.

3.2. Comparisons between groups

Table 4 displays the results of experimental tests for the control group and for LBD patients. LBD patients scored significantly lower than controls on all tests involving tool use (Pantomime of Tool Use: z = 3.26, p = .001; Single Tool Use: z = 3.03, p = .002; Tool-Object Pairs (Choice condition): z = 3.55, p < .001; Tool-Object Pairs (No-Choice condition): z = 2.88, p = .004; Sequential Mechanical Problem-Solving (Choice condition): z = 3.43, p = .001; Sequential Mechanical Problem-Solving (No-Choice condition): z = 2.68, p = .007). Differences between groups were also found in the Tower Of London (z = 2.19, p = .029), Functional and Categorical Associations (z = 2.70, p = .007). However LBD patients did not significantly differ from controls on Recognition of tool utilization gestures (z = 0.67, p = .501).

Table 4 about here

3.3. Correlations between test results in control group

Results are presented in Table 5. Spearman's rank order correlations show relatively few associations between experimental tasks in the control group. A significant association was found between Pantomime of Tool Use and Single Tool Use (*rho* = .55, p < .05). Tower Of London was correlated with Tool-Object Pairs, Choice condition (*rho* = .49, p < .05) and

No-Choice condition (*rho* = .80, $p < .001$) and with Recognition of tool utilization gestures (*rho* = .51, $p < .05$).

Table 5 about here

3.4. Correlations between test results in LBD patients

Results are presented in Table 6. Spearman rank order correlations revealed a strong association between Pantomime of Tool Use, Single Tool Use, Tool-Object Pairs and Sequential Mechanical Problem-Solving (all *rho* > .66, all $p < .004$). Thus, Tool-Object Pairs and Sequential Mechanical Problem-Solving were associated (see Figure 3) in both conditions (Choice and No-Choice). Furthermore, the two conditions (Choice and No-Choice) of Tool-Object Pairs and Sequential Mechanical Problem-Solving were associated in both tests. Significant association (all *rho* > .55, all $p < .028$) was found between Functional and Categorical Associations and Pantomime of Tool Use, Single Tool Use and Tool-Object Pairs (Choice condition and No-Choice condition). Functional and Categorical Associations were also correlated with Sequential Mechanical Problem-Solving for Choice condition (*rho* = .82, $p < .001$) and No-Choice condition (*rho* = .74, $p < .001$). Furthermore, conceptual knowledge of object manipulation (Recognition of tool utilization gestures) showed few associations with tasks involving tool use. Only correlation between Single Tool Use and Recognition of tool utilization gestures reached statistical significance (*rho* = .57, $p = .021$). Performance on the Tower Of London was not correlated with any of the other variables.

Table 6 about here

Figure 3 about here

ALSCAL multidimensional scaling achieved a satisfactory two-dimensional representation (Kruskal's stress = .07, r^2 = .98) which is displayed in Fig. 4. Higher correlations are represented by smaller distances between the respective data points. The distances correspond to the rank order of the correlations but not necessarily to their absolute values. There is a clear separation between Recognition of tool utilization gestures and Tower Of London and the other experimental tasks. Tool Object Pairs in the Choice condition is strongly associated with Sequential Mechanical Problem-Solving in the No- Choice condition. Functional and Categorical Association occupy an intermediate position with equal distance of Tool Object Pairs, No-Choice condition and Sequential Mechanical Problem-Solving in the Choice condition.

Figure 4 about here

In order to investigate which of the correlated variables explained a significant amount of variance in familiar tool use, we carried out a forward regression analysis. Tool-Object Pairs in the Choice condition were used as the dependant variables, and the predictor variables were the score on Pantomime of Tool Use, Sequential Mechanical Problem-Solving (Choice and No-Choice condition) and Functional and Categorical Associations (Tool-Object Pairs in the No-Choice condition and Single Tool Use were excluded because their apparent predictive power could be the result of their similarity with the dependant variable). The analysis showed that the scores on Sequential Mechanical Problem-Solving in the No-Choice condition contributed significantly to the Tool-Object Pairs index in the Choice condition, accounting for 72.2% (p < .0001) of this factor's variance. The association of Sequential Mechanical Problem-Solving in the No-Choice condition and the Functional and Categorical Associations contributed together to the Tool-Object Pairs index in the Choice condition, accounting for 78.4% (p < .0001) of the variance.

4. Discussion

This study proposed to explore the relationships between technical reasoning, semantic knowledge and executive planning in tool use in LBD patients. Our primary interest was the technical reasoning hypothesis which only predict associations between familiar tool use (Tool-Object Pairs) and novel tool use (Sequential Mechanical Problem-Solving).

The main results can be summed up as follows. First, we obtained high correlations between all tasks involving tools. Second, we found no association between Tool-Object Pairs, Sequential Mechanical Problem-Solving, and the Tower Of London. Finally, we found associations between the ability to use tools and knowledge of tool function (Functional and Categorical Associations) but not with knowledge of tool manipulation (Recognition of tool utilization gestures).

4.1. A core mechanism ?

The technical reasoning hypothesis suggests that technical reasoning supports the use of tools in any kind of tool use situation. The key finding of this study is the strong association, in LBD patients, between all tasks involving tools in all conditions. Indeed, our results show that LBD patients were impaired in the use and selection of tools both in Tool-Object Pairs and Sequential Mechanical Problem-Solving. These findings corroborate results observed with the Novel Tool Test that have shown that novel tool selection is impaired in LBD patients (Goldenberg and Hagmann, 1998; Goldenberg and Spatt, 2009; Hartmann et al., 2005). These findings are also consistent with previous correlations between usual and unusual use of tools (Osiurak et al., 2009) in LBD patients. The originality of this study lies nevertheless in the demonstration that LBD patients are impaired for tool selection whether or not they are already familiar with the tool. This is consistent with previous studies showing that LBD patients with apraxia can be perplexed or engage in uncertain explorations when requested to carry out multiple tool use tests (De Renzi and Lucchelli, 1988; Rushworth et al.,

1998) as well as recent studies on Alzheimer patients indicating that distractor tools have an impact on everyday actions (Giovannetti et al., 2010). However, the Choice condition and No-Choice conditions are strongly associated in both tasks (Tool-Object Pairs and Sequential Mechanical Problem-Solving). This result corroborates the results of De Renzi and Luchelli (1988) concerning the high correlation between a multiple object test and a single object test, suggesting that tool use impairment in LBD patients is not completely dependent on the number of tools presented or the number of steps necessary to complete an action (see also Hartmann et al., 2005). Tool use impairments can effectively appear after frontal lobe lesions, or be a consequence of right brain damage or diffuse brain damage (Goldenberg and Hagmann, 1998; Hartmann et al., 2005; Schwartz et al., 1999). In those cases, they are certainly due to visuo-spatial or attentionnal disturbances. We suggest that our results support the view that LBD lesions affect a specific technical reasoning mechanism that operates in every situation requiring the use of a tool. However, to confirm whether our findings are specific to patients with left brain damage, our method will have to be replicated with left and right brain damaged patients.

4.2. Action planning

The executive planning hypothesis suggests that dysexecutive syndrome impacts negatively on everyday tool use, especially in natural actions requiring a preformed plan and the maintenance of goals. The Tool-Object Pairs task does not require a sequence of actions to be achieved. However, the Sequential Mechanical Problem-Solving task does require such a sequence. Difficulties in dealing with novelty and planning problems are also one of the main signs of dysexecutive syndrome. Therefore, in line with the executive planning hypothesis a strong association could be predicted between performance in the Sequential Mechanical Problem-Solving task and in Tower Of London. Our results nevertheless did not corroborate this prediction since no association was found between these two tests. Previous studies had already shown that performance in the Novel Tool Test (Goldenberg and Hagmann, 1998; Goldenberg and Spatt, 2009; Hartmann et al., 2005) can be impaired independently of frontal lobe lesions or dysexective syndrome. Nevertheless, the originality of the present study is to demonstrate that when patients are faced to a sequence of mechanical actions, the role played by executive planning is still minimal.

In sum, executive planning is involved in situations requiring the creation of a mental plan such as in the Tower Of London, but not in situations requiring a sequence of mechanical principles to be achieved. The absence of correlation between Sequential Mechanical Problem-Solving and Tower Of London again supports the technical reasoning hypothesis and strengthens the conclusions of Goldenberg and Hagmann (1998) that the ability to solve mechanical problems is an ability to perform a non-routine task, which nevertheless does not depend on executive functions (see also Goldenberg et al., 2007). Morover, in our study, one patient with frontal lesion (LBD 10) exhibited a deficit in Sequential Mechanical Problem-Solving without deficit in Tower Of London. Anatomo-clinical explorations will be needed to confirm this dissociation between executive planning and mechanical planning in frontal lesions.

4.3. Action representation

As discussed above, the memory hypothesis assumes that knowledge of tool manipulation (gestures engrams) and knowledge of tool functions (semantic memory) support skilled tool use (Buxbaum, 2001; Buxbaum et al., 2003, 2007; Heilman et al., 1982; Rothi et al., 1991; Sirigu et al., 1995). Central to the memory hypothesis is the idea that people acquire knowledge about manipulation and functions of tools with which they had prior experience, so that gesture engrams and semantic memory should be particularly useful when people have to use familiar tools, but not when they have to use novel tools to solve mechanical problems. Our results indicate that both Tool-Object Pairs and Sequential Mechanical Problem-Solving are correlated with Functional and Categorical Associations but not with Recognition of tool utilization gestures. First, these results support dissociation between knowledge of object function and knowledge of object manipulation (Buxbaum et al. 2002). Second, dissociations between tool use impairments (familiar and novel, Choice and No-Choice conditions) and knowledge about tool manipulation provide a new argument against gestures engrams.

4.4. Interactions between technical reasoning and functional knowledge

The technical reasoning hypothesis assumes that technical reasoning supports the use of tool independently of executive planning and semantic memory abilities. Our results partially confirm the technical reasoning hypothesis. Indeed, Functional and Categorical Associations are surprisingly associated with Sequential and Mechanical Problem-Solving. Regression analyses demonstrated that Sequential Mechanical Problem-Solving and Functional and, to a lesser degree, Categorical Associations both contribute to performance on Tool-Object Pairs. These findings are in line with previous studies (Goldenberg and Hagmann, 1998; Randerath et al., 2011; Osiurak et al., 2011) demonstrating the involvement of both, semantic memory and technical reasoning in actual use of familiar tools.

One possible explanation for the association between technical reasoning and memory related processes (functional knowledge) in the use of familiar and novel tools is that humans first try to operate with familiar solutions they have encountered from previous experience. Functional and categorical knowledge could potentially be recruited in order to find solutions based on similarity with previous experience. That might sometimes be useful especially for single steps, when the end of the action is clear or very similar to previous experience. However, technical reasoning is necessary when the solution is less predefined, for example when participants also have to select one out of several presented tools to complete the action or to determine what steps are needed to achieve the goal. In those cases, real time analysis of mechanical relationships between possible technical means and possible technical ends is needed and potentially related to previous experience (memory related processes). In this framework, semantic memory might, at least in part, guide the behavior of patients by allowing them to select the usual tool corresponding to a given object. But, as our results indicated, even if this interpretation still implies a minimal role of semantic memory, this kind of knowledge would be far from necessary, since LBD patients also failed the No-Choice condition in which a tool was directly presented with the corresponding object on which it was to be used. Thus, the following hypothesis can be formulated: when technical reasoning is strongly deficient, functional knowledge is not sufficient to support tool selection and tool manipulation because the purpose of the action cannot be identified.

Goldenberg (2009) suggested that "imitation of gestures and use of tool and objects depend on left parietal lobe integrity because of their demands on categorical apprehension of spatial relationships between multiple objects". It would be interesting to analyze the relationships between imitation of postures and Sequential Mechanical Problem-Solving and to re-examine the issue of the dorsal stream (see also Buxbaum, 2001) in light of the technical reasoning hypothesis.

Finally, the correlation between Pantomime of Tool Use and Sequential Mechanical Problem-Solving is equally noteworthy. Pantomime of tool use is a classical test in clinical neuropsychology traditionally associated with semantic memory (Goldenberg and Hagmann, 1998). Goldenberg et al. (2003) demonstrated that it is not a specific task due to its correlation with a variety of other verbal and non-verbal tasks dependent on left hemisphere function. According to this, we suggest that technical reasoning can play a role in pantomime of tool use even if tools are not physically present. Moreover, our results are in line with results of Goldenberg and Hagmann (1998) showing a correlation between pantomime of tool use and novel tool selection.

5. Conclusion

In sum, all tasks involving tools are strongly associated in LBD patients. The ability to solve sequential mechanical problems does not depend on executive planning. Also, familiar and novel tool use are associated with knowledge about object function but not with knowledge about tool manipulation. Our findings provide new evidence for the theory that although human tool use may involve conceptual knowledge, it is likely to be supported primarily by technical reasoning. It is noteworthy that somewhat similar proposals have already been formulated in other fields of psychology. For instance, Penn et al. (2008) suggested that unlike non-human primates, including those primates known to be tool users in the wild, humans are able to reinterpret the physical world in terms of abstract principles and that this ability could be the basis for human tool use. Studies in developmental psychology also demonstrate that tool use and innovation are independent from acquired conceptual knowledge and executive functioning (Beck et al. 2011; Defeyter et al., 2003). The present results therefore encourage us to continue in this direction and to incorporate data from comparative or developmental psychology in the study of technical reasoning.

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Footnote 1

Example for the box C: instead of making lever, some subjects in the Choice condition unfolded the long metal rod (Figure 2) in order to bring the target to the entrance of the box. This action was impossible in the No-Choice condition since only a rigid rod was given. Regardless of whether subjects made lever or unfolded the long metal rod, two actions were nevertheless necessary to extract the target (bringing the target to the entrance of the box and bringing out the target from the entrance of the box).

Table 1 – Deficits' predictions in LBD patients according to each hypothesis.

	TOP C	TOP NC	SMPS C	SMPS NC	TOL	Reco	FCA
Semantic memory hypothesis:	(-)	(-)	(+)	(+)	(+)	(-)	(-)
Executive planning hypothesis:	(+)	(+)	(-)	(-)	(-)	(+)	(+)
Technical reasoning hypothesis:	(-)	(-)	(-)	(-)	(+)	(+)	(+)

Abbreviations: TOP C, Tool-Object Pairs "Choice condition"; TOP NC, Tool-Object Pairs "No-Choice condition"; SMPS C, Sequential Mechanical Problem-Solving "Choice condition"; SMPS NC, Sequential Mechanical Problem-Solving "No-Choice condition"; TOL, Tower Of London; Reco, Recognition of tool utilization gestures; FCA, Functional and Categorical Associations.
(+) : No deficit
(-) : Deficit

Table 2 – Demographical and clinical data.

	LBD (n = 16)	Control (n = 19)	LBD vs. control
Gender (no.): women/men	8/9	14/5	ns
Age (years)	70.2 (10.3)	69.4 (7.7)	ns
Education (years)	10.9 (4.3)	8.9 (2.1)	*
Type of CVA: ischemia / bleeding	14/2	-	
Time since CVA (days)	16.06 (12.38)	-	
Hemiparesis (no.): none/paresis/plegia	8/5/3	-	
Hemianopia (no.): present/absent	6/10	-	

Between-group comparisons were performed with Student's *t*-test, except for "gender" (χ^2 analyses). Values in brackets are standard deviations.

* $p < .05$

Table 3 – Tower Of London scoring system.

Items	Minimum number of moves	Success within 2 minutes			Failure
		3 Points	2 Points	1 Point	0 Point
1	2	2		3 and more	
2	3	3	4	5 and more	
3	4	4	5-6	7 and more	
4	5	5	6-7-8	9 and more	
5	6	6-7	8-9-10-11	12 and more	
6	7	7-8	9-10-11-12-13	14 and more	

Table 4 – Results of experimental tests in controls and LBD patients.

	PTU	STU	TOP C	TOP NC	SMPS C	SMPS NC	TOL	Reco	FCA	Lesions
	(20)	(20)	(20)	(20)	(9)	(9)	(18)	(10)	(20)	
Controls										
Mean	17.32	18.68	19.68	19.84	8.26	8.37	15.58	9.05	19.05	
Standard deviation	2.13	1.87	0.65	0.36	0.85	0.98	1.27	0.94	1.05	
Range	14-20	13-20	18-20	19-20	7-9	6-9	13-18	6-10	17-20	
Median	17	19	20	20	9	9	15	9	19	
5^{th} Percentile	14	15.7	18	19	7	6	13.9	7.8	17	
LBD 1	18	7*	18*	18	3*	9	6*	9	18	T, P, BG
LBD 2	7*	10*	8*	14*	1*	7	16	7*	8*	F, T, P, BG
LBD 3	3*	14*	19	20	7	7	17	8	18	P
LBD 4	12*	16	20	19	4*	8	16	9	20	F, P
LBD 5	19	20	19	20	9	9	17	9	20	T, O
LBD 6	18	19	15*	20	3*	6	12*	9	10*	F, T, P, BG
LBD 7	18	20	20	20	9	9	15	10	20	P
LBD 8	13*	17	20	20	9	9	15	9	20	P, BG
LBD 9	0*	3*	0*	2*	0*	1*	11*	9	3*	BG
LBD 10	0*	16	6*	12*	2*	3*	16	10	17	F
LBD 11	0*	5*	6*	12*	1*	3*	12*	6*	8*	F, T, P, BG
LBD 12	2*	5*	6*	12*	1*	3*	13*	6*	8*	T, P
LBD 13	5*	16	18	20	3*	5*	12*	7*	17	T, O
LBD 14	17	17	20	20	8	9	12*	10	17	F, P
LBD 15	5*	15*	13*	18*	4*	4*	14	10	18	F, P
LBD 16	14	19	16*	18*	5*	5*	14	10	9*	F, T, P
Mean	9.44	14.31	14	16.56	4.31	6.06	13.62	8.63	14.44	
Standard deviation	7.15	5.36	6.61	5.01	3.16	2.69	2.82	1.36	5.51	

Scores in brackets are maximum values.

* Scores below the 5^{th} percentile.

Abbreviations: F, frontal; P, parietal; T, temporal; O, occipital; BG, basal ganglia. PTU, Pantomime of Tool Use; STU, Single Tool Use; TOP C, Tool-Object Pairs "Choice condition"; TOP NC, Tool-Object Pairs "No-Choice condition"; SPMS C, Sequential Mechanical Problem-Solving "Choice condition"; SPMS NC, Sequential Mechanical Problem-Solving "No-Choice condition"; TOL, Tower Of London; Reco, Recognition of tool utilization gestures; FCA, Functional and Categorical Associations.

Table 5 – Correlations between tests results (Spearman Rho) in control group.

	STU	TOP C	TOP NC	SMPS C	SMPS NC	TOL	Reco	FCA
Pantomime of Tool Use	.55*	.03	.023	.40	.30	.08	.02	.03
Single Tool Use (STU)		.34	.22	.42	.23	.10	.35	.11
Tool-Object Pairs “Choice condition” (TOP C)			.80**	.07	.38	.49*	.50*	.08
Tool-Object Pairs “No-Choice condition” (TOP NC)				.27	.32	.49*	.30	.12
Sequential Mechanical Problem-Solving “Choice condition” (SMPS C)					.04	.03	.11	.00
Sequential Mechanical Problem-Solving “No-Choice condition” (SMPS NC)						.26	.10	.06
Tower Of London (TOL)							.01	.21
Recognition of tool utilization gestures (Reco)								.34
Functional and Categorical Associations (FCA)								-

**$p < .01$
* $p < .05$

Table 6 – Correlations between tests results (Spearman Rho) in LBD patients.

	STU	TOP C	TOP NC	SMPS C	SMPS NC	TOL	Reco	FCA
Pantomime of Tool Use	.88*	.67**	.68**	.67**	.83**	.05	.37	.58*
Single Tool Use (STU)		.66**	.69**	.76**	.70**	.16	.57*	.61*
Tool-Object Pairs "Choice condition" (TOP C)			.85**	.88**	.88**	.31	.31	.81**
Tool-Object Pairs "No-Choice condition" (TOP NC)				.82**	.75**	.25	.19	.68**
Sequential Mechanical Problem-Solving "Choice condition" (SMPS C)					.77**	.43	.50	82**
Sequential Mechanical Problem-Solving "No-Choice condition" (SMPS NC)						.26	.25	.74**
Tower Of London (TOL)							.08	.48
Recognition of tool utilization gestures (Reco)								.38
Functional and Categorical Associations (FCA)								-

**$p < .01$

* $p < .05$