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USING TOOLS EFFECTIVELY DESPITE DEFECTIVE HAND POSTURE: A SINGLE-CASE STUDY

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Abstract

Apraxia, a cognitive disorder of motor control, can severely impair transitive actions (object-related) and may lead to action errors (e.g., rubbing a hammer on a nail instead of pounding it) and hand posture errors (e.g., grasping a tool in a wrong way). Here, we report a rare observation of a left-handed patient, left-lateralized for language, who developed a severe apraxia following a right brain lesion. Interestingly the patient showed a significant number of hand posture errors, while she perfectly demonstrated the actual use of tools. This case stressed the predictions made by the current theories of tool use. According to the manipulation-based approach, the hand posture errors should be associated with an impaired manipulation knowledge. According to the reasoning-based approach, the absence of action errors should be associated with spared mechanical knowledge. Moreover, to better understand the neurocognitive origins of the deficit observed in VF, we examined several potential brain lateralization of praxis functions. We initiated a systematic examination of VF's performance in several contexts of tool use allowing us to investigate which kinds of tool-use representations were potentially impaired in VF. Our investigation did not reveal any major deficit of manipulation knowledge. This can hardly account for the high frequency of hand posture errors, contrary to the predictions of the manipulation-based approach. In contrast, in line with the reasoning-based approach, mechanical knowledge was spared and can explain the absence of action errors. We also found that VF probably had a bilateral organization of praxis functions, but irrespective of the possible brain lateralization considered, none of which established a satisfactory association between manipulation knowledge and hand posture errors. Taken together, the manipulation-based approach fails to explain fully the deficit presented by this patient and should lead us to consider alternative explanations.

Keywords: tool use; apraxia; action errors; hand posture errors; manipulation knowledge

1. Introduction

Apraxia is a cognitive disorder of motor control which cannot be explained by elemental motor deficits nor by general cognitive impairment (De Renzi & Lucchelli, 1988). Apraxia can severely impair transitive (tool-related) actions and, at a lesser extent, intransitive actions (Goldenberg & Hagmann, 1997). In the case of transitive actions, two kinds of errors can be identified. The first concerns the ineffectiveness of the “action” performed (hereafter called action errors). Action errors are observed when apraxic patients cannot demonstrate how to use a tool with the corresponding object (i.e., real tool use; Goldenberg & Hagmann, 1998; Jarry et al., 2013; Osiurak, Aubin, Allain, Jarry, Richard, et al., 2008; Osiurak, Jarry, Lesourd, Baumard, & Le Gall, 2013). For instance, patients may try to rub a hammer on a nail instead of pounding it with the hammer. In action errors, the relation between the tool and the object is impaired (i.e., tool-object representation). The second kind of errors concerns difficulties to perform the appropriate handgrip (e.g., grasping a tool in a wrong way; i.e., the postural component of gestures; hereafter called hand posture errors). Hand posture errors can be found in pantomime of tool use or when shaping the hand for grasping tools (Buxbaum, Kyle, & Menon, 2005). In hand posture errors, the relation between the hand and the tool is impaired (i.e., tool-hand representation).

Several cognitive representations have been identified to support the ability to use tools, that is, functional knowledge (i.e., semantic knowledge about tool use; Gonzalez Rothi, Ochipa, & Heilman, 1991), mechanical knowledge and manipulation knowledge. Functional knowledge is tool-centered, as it stores information about tools in relation to their purpose and their recipient (e.g., Goldenberg, 2013). Mechanical knowledge is tool-object centered, as it is based on the understanding of opposition existing between physical properties of tools and objects (Osiurak, Jarry, & Le Gall, 2010; Osiurak, 2014). Manipulation knowledge (also called gesture engrams; Buxbaum, 2001) is tool-hand centered as it stores information about

how to manipulate tools (e.g., knowing that the use of a hammer is associated with oscillations of the elbow) but it is not contextualized so that damage to manipulation knowledge leads to impairment in both gesture production and gesture recognition. Activation (fMRI) studies showed that mechanical, functional and manipulation knowledge are supported by a large brain network predominantly located in the left hemisphere (Boronat et al., 2005; Canessa et al., 2008; Ishibashi, Pobric, Saito, & Lambon Ralph, 2016; Reynaud, Lesourd, Navarro, & Osiurak, 2016; van Elk, 2014). In line with fMRI data, studies of brain-damaged patients showed that apraxia is commonly observed in left brain-damaged (LBD) patients (Baumard et al., 2014; Niessen, Fink, & Weiss, 2014). Functional knowledge can be disrupted following left temporal lobe lesions (Goldenberg & Spatt, 2009; Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000), mechanical knowledge can be impaired following inferior parietal lobe (IPL) lesions (Goldenberg & Spatt, 2009; Jarry et al., 2013), and manipulation knowledge is also impaired following left IPL¹ lesions (Buxbaum, 2001; Buxbaum, Kyle, Grossman, & Coslett, 2007). Unlike LBD patients, it has been found that right-brain damaged (RBD) patients are almost unaffected by apraxic deficits (Buchmann & Randerath, 2017; Randerath, Li, Goldenberg, & Hermsdörfer, 2009).

In the present study, we report the rare observation of VF, a female patient, left-handed and left-lateralized for language, who developed a severe apraxia following an ischemic stroke affecting the right hemisphere. VF is particularly impaired for both (1) pantomiming

¹ A recent VLSM study in LBD patients reported that postural components of gestures were impaired following lesions in the left pMTG, whereas kinematic components of gestures were impaired following lesions in the left IPL (Buxbaum, Shapiro, & Coslett, 2014). Thus, postural and kinematic components of manipulation knowledge may rely upon distinct cerebral networks, not only located within the left IPL.

the use of tools; and (2) recognizing/producing correct hand posture for grasping tools. Of particular interest is the presence and frequency of hand posture errors in the apparent absence of action errors in real tool use tasks (see **Fig.1**). In broad terms, VF grasps the tools with inaccurate hand postures, but uses the tools in an effective manner. This case is highly interesting for several reasons.

< Insert **Figure 1** about here >

First, this case of apraxia questions the predictions made by the current theories of tool use. According to the manipulation-based approach (MBA; Buxbaum, 2001), the presence of hand posture errors in VF in pantomime and real tool use tasks should be well explained by a severe damage or impaired access to manipulation knowledge. For instance, the patient LL (Sirigu et al., 1995) who presented the same hand posture deficit as VF, showed hand posture errors in both pantomime and real tool use tasks in association with defective manipulation knowledge. However, VF and LL are rare cases reported in the literature with this kind of impairment (see also Hayakawa, Fuji, Yamadori, Meguro, & Suzuki, 2015). Indeed, while hand posture errors are commonly reported in pantomime of tool use in apraxic patients (e.g., Buxbaum et al., 2007), they are rarely observed in real tool use tasks (Osiurak, Aubin, Allain, Jarry, Etcharry-Bouyx, et al., 2008; Randerath, Goldenberg, Spijkers, Li, & Hermsdörfer, 2010; Randerath et al., 2009). Thus, in apraxic patients, if defective manipulation knowledge is a good predictor of hand posture errors in pantomime of tool use task, this is less obvious in real tool use task, where both the tools and the corresponding objects are available.

Additionally, if hand posture errors are rare in real tool use tasks, they are nevertheless systematically followed by action errors (Randerath et al., 2010). However, VF produces few action errors following hand posture errors, suggesting the existence of a dissociation between tool-hand and tool-object representations. MBA can hardly explain why a severe damage of manipulation knowledge is not associated with a deficit for using tools, unless assuming

either that manipulation knowledge is not necessary for the actual use of tools (Osiurak & Badets, 2016; Osiurak et al., 2009, 2010; Osiurak, Jarry, & Le Gall, 2011) or invoking additional compensatory processes (i.e., production system). In contrast, the reasoning-based approach (RBA; Osiurak & Badets, 2016), assumes that the ability to use tools largely depends on mechanical knowledge (i.e., tool-object representations). In broad terms, RBA assumes that using tools relies firstly upon the integrity of tool-object representations. As VF commit few action errors, the preservation of mechanical knowledge should explain why she actually can properly use familiar tools, despite high frequency of hand posture errors.

Second, the side of the lesion in the right hemisphere associated with the praxis deficit raises the question of the brain organization of representations supporting tool use in a patient who is left-handed and left-lateralized for language. In left-handers, patients without aphasia are rarely concerned with apraxic deficits. For instance, it has been found that only 14% (n = 3/21) had pantomime of tool use impairment and only 10% (n = 2/21) had tool use deficit² (Goldenberg, 2013b). Moreover, only two other cases of left-handed patients with apraxia following right-brain lesion have been described in the literature (Margolin, 1980; Ochipa, Rothi, & Heilman, 1989), but at the time, no extensive investigation of tool use tasks (i.e., pantomime of tool use, single tool use and real tool use), and of representations supporting tool use (i.e., functional knowledge, manipulation knowledge, and mechanical knowledge) were done. Thus, in the present paper, we examined the performance of VF in several contexts of tool use, as well as with tasks allowing us to investigate the representations

² However, in the study of Goldenberg (2013), it is not specified whether the impairment observed in left-handers without apraxia in the tool use task, concerns inaccurate hand postures (tool-hand representations) or/and inability to use the tools with the objects (tool-object representations).

supporting tool use, to better understand the neurocognitive origins of the deficit of this patient. We examined the pattern of performance of VF with three potential brain organization of praxis functions, given a left-lateralization of language: (1) lateralization of praxis functions in the right hemisphere and lateralization of language in the left hemisphere (i.e., crossed-apraxia; Margolin, 1980); (2) co-lateralization of language and praxis functions in the left hemisphere (Vingerhoets et al., 2012; Vingerhoets, Alderweireldt, Vandemaele, & Cai, 2013); and finally (3) bilateral brain organization of praxis functions with a lateralization of language in the left hemisphere (e.g., Subject 4 in Króliczak, Piper, & Frey, 2011).

To sum up, the aim of the present case study was to stress some predictions made by the current theories of tool use regarding the performance of VF, that is, (1) according to the MBA, a high frequency of hand posture errors should be associated with a defective manipulation knowledge; and (2) according to RBA, the absence of action errors should be associated with the preservation of mechanical knowledge. We also compared the performance of VF with a sample of apraxic LBD patients, non-apraxic LBD patients and RBD patients. Finally, we examined the integrity/deficit of representations supporting tool use in VF, regarding three potential brain organization (i.e., lateralization) of praxis functions. Based on our findings, we will propose different interpretations and discuss their implications for the current theories of tool use.

2. Case report

2.1. The patient

VF, a 47 years old woman with 8 years of education was working as a florist for 10 years when she underwent, in August 2014, an ischemic stroke affecting the right hemisphere. The following areas of the right hemisphere were damaged: the superior, middle and inferior frontal gyri including the orbital, triangular and opercular parts, the rolandic operculum, insula, lenticular and caudate nuclei, the ventrolateral part of precentral and postcentral gyri,

the superior, middle and inferior temporal gyri, the supramarginal gyrus, the angular gyrus and the anterior part of the intraparietal sulcus (see **Fig.2**). VF presented a NIHSS (National Institute of Health Stroke Score) of 16/42 at her arrival in the unit and could benefit from an intravenous thrombolysis. Three weeks after her stroke, VF was admitted to the medical and physical rehabilitation center (MPR; CHU Grenoble Alpes) for four months and one week.

< Insert **Figure 2** about here >

VF came to our attention fifteen months after her stroke. Her main complaints were to be uncomfortable when using some tools (e.g., broom) and to be highly fatigable. These difficulties were corroborated by her husband. Moreover, her husband reported that VF could hold familiar tools in an awkward way (i.e., unusual hand posture while holding a tool) since her stroke. At the time of the examination VF was not able to take back her professional activity. VF did not present signs of anxiety nor depression with a HAD score of 7/30 and she did not have any cognitive complaints with a QPC score of 1/8. Handedness assessment with the Edinburgh Handedness Inventory (Oldfield, 1971) indicated a marked left hand preference (score of -100%).

2.2. Preliminary neuropsychological evaluation

The neuropsychological assessment was carried out fifteen months after the stroke in November 2015 and aimed: (1) to characterize the global cognitive functioning; and (2) to give a preliminary praxis examination.

The neuropsychological assessment (**Table 1**) revealed several cognitive impairments that were not reported spontaneously by the patient and did not correspond with the low score obtained at the cognitive complaints scale (QPC = 1/8). General intellectual ability was in the low range and may correspond at least in part to the low educational level of the patient. Nevertheless, non-verbal reasoning was limited given the Perceptual Reasoning Index (WAIS-IV; Wechsler, 2008). VF presented a marked deficit in verbal long-term memory

attested by pathological scores in recognition and free recall in the California Verbal Learning Test (CVLT; Delis, Kramer, Kaplan, & Ober, 1987) but normal scores in the Doors Test (Baddeley, Emslie, & Nimmo-Smith, 1994) suggested spared visual modality of long-term memory. Moreover, normal forward and backward auditory digit span (Wechsler, 2008), as well as normal forward and backward visuospatial span (Corsi, 1972) indicated spared short-term and working memory, respectively. A dysexecutive syndrome was also found, attested by pathological scores obtained at the Trail-Making Test (flexibility), the Hanoi tower (planification) and the Brixton test (rule detection; Burgess & Shallice, 1997). Concerning language, VF presented fluent and well-articulated spontaneous language. Comprehension seemed to be normal and was confirmed, at least for simple commands, by her performance on the Token Test (De Renzi & Faglioni, 1978). Scores in normal range for semantic and phonemic fluency indicated a normal verbal fluency and good search strategies in semantic memory. Moreover, VF showed a left-lateralization of brain activation for language (see Supplementary material **Fig.1**), as it was observed when VF underwent a denomination of picture task during fMRI scanning. In the visuo-spatial domain, VF met difficulties in the Bells test (Gauthier, Dehaut, & Joannette, 1989), with several omissions in the left part, which is possibly related to sequelae of visual neglect. We also found poor copy of the Taylor complex figure (Taylor, 1969) which can be associated with visuo-constructive impairment but also with difficulties in programming the copy of the figure. Finally, VF presented a bimanual motor weakness, a loss of dexterity only with the left hand and an inability to execute motor sequences (fist-edge-palm).

< Insert **Table 1** about here >

Table 2 summarizes the results obtained with the preliminary praxis evaluation (TLA; Anicet, Calais, Lefevre, & Rousseaux, 2007). VF was largely impaired when she was asked to produce transitive and intransitive gestures whatever the modality (i.e., imitation or verbal

command). However, the ability to name and discriminate gestures according to their meaning were preserved, as well as functional knowledge. During pantomime of tool use, VF made characteristic errors observed in apraxia, that is, recognizable gestures containing spatiotemporal errors (e.g., stereotypic movement, body part object, etc.). Moreover, when asked to use tools in isolation (i.e., single tool use), VF grasped the tools in an awkward way, as it has been previously observed with the case LL (Sirigu et al., 1995; see **Fig. 1.a-c**). Interestingly, the hand posture deficit seemed to persist in real tool use situation (i.e., using a tool with an object), for instance, when VF was asked to cut a piece of paper with a scissor, despite a very uncomfortable hand posture, VF successfully cut the piece of paper (**Fig.1.d-e**). This observation suggests that all the components of transitive actions are not impaired in VF, that is, impaired tool-hand relationship (i.e., presence of hand posture errors) and spared tool-object relationship (i.e., absence of action errors).

< Insert **Table 2** about here >

3. Experimental studies

The experimental investigations took place between January 2016 and April 2016. For each experiment, raw data are provided in Supplementary Material **Table 1-6**. We report how we determined our sample size in the LBD-A, LBD-NA, and RBD comparison groups, all data exclusions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

3.1. Use of familiar tools

We investigated the use of familiar tools with three classical tasks, namely, pantomime of tool use, single tool use and real tool use tasks. In these tasks, the performance of VF was compared with three groups of brain-damaged patients (see **Table 3**): LBD apraxic (LBD-A;

$n = 8$), LBD non-apraxic (LBD-NA; $n = 7$) and RBD ($n = 5$)³. These patients were selected because (1) they were previously assessed on the same tasks including the same familiar objects used in the present study; and (2) they were matched as closely as possible in terms of age and educational level with VF.

< Insert **Table 3** about here >

3.1.1. Pantomime of tool use (PTU) and single tool use (STU) tasks

Methods. Ten familiar tools (hammer, jug, electrical plug, match, bottle opener, saw, scissors, key, screwdriver, bulb) were presented, one at a time on a vertical panel. VF was asked to demonstrate the typical use of the tools with the left hand: (1) without holding them in the PTU task; and (2) with holding them in the STU task. All patients started with the PTU task followed by the STU task.

The examiner did not name the tools. Performance was videotaped and each gesture was scored dichotomously (correct/incorrect) in four categories: Hand posture, Arm posture, Amplitude and Timing (see Buxbaum, Giovannetti, & Libon, 2000). Each correct component of gesture was given 1 point (4 points maximum for each gesture).

The performance of VF in PTU and STU tasks was scored by two independent coders. Interrater agreement was assessed using Cohen's Kappa and mean interrater agreement for all gesture components was 80% (Hand posture = 85%, Arm posture = 77%, Amplitude = 78%, Timing = 79%). Concerning brain-damaged patients, the same independent raters coded 11 videos (the half of the whole data) for PTU and STU tasks. Mean interrater agreement for all gesture components was 82% (Hand posture = 86%, Arm posture = 84%, Amplitude = 79%,

³ The apraxic and non-apraxic LBD patients were described in a previous work of our group (Jarry et al., 2013) and RBD patients are part of an unpublished study (Jarry et al., unpublished).

Timing = 80%). Scores for which there was disagreement were reconciled by additional review of videotapes.

We focused our analyzes on the accuracy for the Hand posture component. Between-group comparisons were calculated with Mann-Whitney U tests, within-group comparisons were calculated with Wilcoxon matched pairs tests. The presence of a deficit in VF was tested with Crawford-Howell modified t -tests (Crawford & Howell, 1998) and the presence of differences among VF's performance was tested with the Revised Standardized Difference Test (RSDT; Crawford & Garthwaite, 2005).

Results. The results are displayed in **Fig.3**. First, we observed that LBD-A patients had Hand posture performance significantly lower than LBD-NA and RBD for both PTU ($z = -3.13, p < .01$ and $z = -2.84, p < .01$, respectively) and STU ($z = -3.07, p < .01$ and $z = -2.76, p < .01$, respectively). Nevertheless, LBD-A significantly improved their performance between PTU and STU for the Hand posture component ($z = 2.11, p < .05$). Second, when comparing VF's performance to LBD-A, we found that Hand posture scores were similar in VF (30%) and LBD-A ($M = 30.0\%$, $SD = 15.3$; $t = 0, p = .50$) in the pantomime of tool use task, but Hand posture scores were significantly higher for LBD-A compared to VF (30%) in the STU task ($M = 74.3\%$, $SD = 15.1$; $t = -2.77, p = .014$). Third, Crawford and Garthwaite's (2005) RSDT was applied to test whether the difference between VF's scores on Hand posture on PTU and STU tasks is significantly different from the differences observed in LBD-A. The results showed that VF's pattern of performance fulfils the criteria for a classical dissociation (RSDT: $t = 2.40, p = .02$). Indeed, VF's performance was not improved between PTU and STU in contrast to LBD-A.

< Insert **Figure 3** about here >

3.1.2. Real tool use task

Methods. This task is made of the same ten familiar tools used in PTU and STU tasks and the corresponding objects upon which they can be used (hammer-nail, jug-glass, electrical plug-electrical socket, match-matchbox, bottle opener-bottle, saw-piece of wood, scissors-thread, screwdriver-screw, key-lock in a wooden board, bulb-bulb socket). VF was asked to actually use the tool with the corresponding object. The examiner did not name the tools, the objects or actions to be done. In the real tool use in choice condition (RTU-C), VF was given one object in front of her and was asked to (1) select the associated tool; and (2) to use the tool with the object. The time limit was set to 60s and two scores were calculated: a hand posture score and an action score. The hand posture score was calculated by dividing the number of correct hand postures by the total number of correct selected tools. The action score was calculated by dividing the total number of correct actions (each time a tool was successfully used with the associated object; maximum = 10 points) by the total number of items ($n = 10$).

Additionally, we proposed to VF the same task in a no-choice condition (RTU-NC; Lesourd, Baumard, Jarry, Le Gall, et al., 2017) where only the tool and the corresponding object were presented. Finally, the examiner correctly positioned the VF fingers on the tools and VF was instructed, by maintaining her hand posture, to show the correct use of the tool (see for example Task II: hand posture correction; Sirigu et al., 1995).

VF scores were compared to LBD-A, LBD-NA and RBD patients only on the RTU-C task. Comparisons were made using Crawford-Howell modified t -tests (Crawford & Howell, 1998). We also test whether the difference between VF's scores on Grip accuracy and on Action accuracy was significantly different from the differences observed in LBD-A with the RSDT (Crawford & Garthwaite, 2005). Additionally, to assess the association between hand posture score and action score, Phi correlation coefficients for dichotomous variables were calculated, within each group of patients, between hand posture accuracy (0 or 1:

incorrect/correct grip) and action accuracy (0 or 1: incorrect/correct action). VF started with RTU-C followed by RTU-NC task and hand posture correction task in this order.

Results. As it can be seen in **Fig.4**, in the RTU-C task, considering action accuracy, VF (90%) performed as RBD ($M = 96\%$, $SD = 5.5$; $t = -.99$, $p = .19$) and LBD-NA ($M = 91.4\%$, $SD = 9.0$; $t = -.15$, $p = .45$) and had a higher score than LBD-A even if it was not significant ($M = 46.3\%$, $SD = 27.2$; $t = 1.51$, $p = .08$). Considering hand posture accuracy, VF (50%) performed significantly lower than the three groups of patients (RBD: $M = 98\%$, $SD = 4.5$; LBD-NA: $M = 95.6\%$, $SD = 5.6$; LBD-A: $M = 86.4\%$, $SD = 11.2$; *all* $t < -3.01$, *all* $p < .05$). When we compared specifically the performance of VF and LBD-A patients, we found a significant dissociation, that is, VF's performance was improved between Hand posture accuracy and Action accuracy whereas LBD-A patients showed the reverse pattern (RSDT: $t = 4.31$, $p = .004$). VF selected a similar number of non-relevant tools ($n = 1$; selection errors) compared to all other groups (RBD: $M = .6$, $SD = 1.34$; LBD-NA: $M = .29$, $SD = .49$; LBD-A: $M = 5.5$, $SD = 4.41$; *all* $|t| < 1.36$, *all* $p > .11$). VF obtained exactly the same performance in the RTU-NC task as in the RTU-C task, where only one tool and the associated object were proposed simultaneously (action accuracy: 90% and hand posture accuracy: 50%). Moreover, we observed hand posture errors for the same tools in both RTU-C and RTU-NC tasks. Finally, in the hand posture correction task when the examiner positioned correctly the fingers of VF on the tools, the patient showed correctly the use of all the tools ($n = 10/10$), even when the hand posture was previously incorrect.

< Insert **Figure 4** about here >

We found a significant association between action accuracy and hand posture accuracy for LBD-A patients ($\phi = .58$, $\chi^2 = 10.72$, $df = 1$, $p < .05$) but not for LBD-NA patients ($\phi = .29$, $\chi^2 = 1.18$, $df = 1$, $p = .28$). There was a trend toward significance for the difference between the correlation coefficients for LBD-A and LBD-NA ($z = 1.87$, $p = .07$). RBD

patients produced neither grip errors nor action errors during RTU-C task, preventing us to calculate the association coefficient between hand posture accuracy and action accuracy.

3.1.3. Summary of the results

VF and LBD-A patients were equally impaired in PTU task for hand posture compared to LBD-NA and RBD patients, suggesting that apraxia specifically impairs hand-tool relationships (Buxbaum et al., 2007; Buxbaum et al., 2003). However, whereas LBD-A patients improved significantly their hand posture with the tool in hand, which is commonly observed with apraxia (for a review see Baumard et al., 2014), this was not the case for VF. Moreover, in the RTU-C task, where the tools had to be used with the associated objects, VF produced a significant number of hand posture errors but did not show action errors.

We also found a significant association between hand posture errors and action errors in LBD-A. Consistent with our findings, Randerath et al., (2010) reported in a grasping to use task (i.e., single tool use task), that hand posture errors were strongly associated with action errors in LBD patients. However, if hand posture errors (also called non-functional grips) are more frequent in LBD than in RBD patients, this behavior remains rare in LBD patients (Osiurak et al., 2008; Randerath et al., 2009). Surprisingly, VF produced more hand posture errors than LBD-A patients, without impacting the correct achievement of tool use actions. We propose to further investigate the grasping components of action in VF, namely, grasping to transport and grasping to use (see Osiurak et al., 2008 for a similar task). These tasks will test the specificity of the hand posture impairment (i.e., familiar tool use vs novel tool use) and should confirm the lack of association observed between action errors and grip errors.

3.2 Grasping components of action: transport and use

3.2.1. Grasping-to-transport condition

Method. VF sat at a table upon which was fastened a cradle that included two supports (see **Fig.5A**). A red-and-blue wooden dowel (length 32cm, diameter 2cm) laid on supports with the blue end on the left support. To each side of the dowel laid a red and a blue disk (diameter 3cm). VF began each trial with the hand resting in a neutral orientation (thumb pointing to 12 o'clock). When the examiner pointed to a red (blue) disk, VF was required to pick up the dowel and place the red (blue) end squarely on the red (blue) disk. Each disk was pointed 6 times, totaling 24 trials. VF performed the grasping-to-transport condition with the left hand (24 trials) and the right hand (24 trials). VF was told to use a power grip and not to twirl the dowel. To prevent the patient from seeing appropriate grips, the examiner moved the dowel by holding it between the index and the middle finger of each hand, with the palms facing each other. Two final postures were distinguished at the time the dowel was placed on the disk, that is, a comfortable final posture corresponded to the thumb pointing up, and an uncomfortable final posture to the thumb pointing down. Two initial grips were distinguished at the time the dowel was grasped: an overhand or an underhand grip (Rosenbaum et al., 1990).

< Insert **Figure 5** about here >

Results. In the grasping-to-transport condition, VF performed only one uncomfortable final posture ($n = 47/48$) made with the left hand (left hand: $n = 23/24$, right hand: $n = 24/24$). Moreover, the distribution of overhand (left hand: $n = 13/24$, right hand: $n = 12/24$) and underhand (left hand: $n = 11/24$, right hand: $n = 12/24$) grips did not differ significantly between both hands ($\chi^2 = .17$, $df = 3$, $p = .98$).

3.2.2. Grasping-to-use condition

Method. VF sat at a table upon which were placed a familiar object and the corresponding recipient (see **Fig.5B**). VF began each trial with the hand resting on the desk in a palm down position. VF completed the task with her left hand first and then with her right

hand. Her thumb pointed to either the 3 o'clock position (left hand) or the 9 o'clock position (right hand). VF was instructed to pick up the tool and to demonstrate how she uses it with the recipient. It was stressed that the grip should remain unchanged once VF picked up the tool. Tool orientation was manipulated: the handle toward (**Fig.5B1**) versus away from VF (**Fig.5B2**). To prevent VF from seeing appropriate grips, the examiner moved the tools by holding them between the index and the middle finger of each hand, with the palms facing each other. Each tool was presented 4 times in each orientation totaling 112 trials (7 tools/recipients x 2 orientations x 4 trials x 2 hands). Two handgrips were identified: a functional grip occurred if the handle was grasped with the thumb toward the active part of the tool and a non-functional grip, if the handle was grasped with the thumb away from the active part. An ANOVA for single case studies (Q' test; Michael, 2007) were carried out on percentage of functional grips (i.e., number of functional grips/total of grips x 100) relative to the orientation of the tool (handle forward vs handle away) and of the hand (left vs right). We were also concerned with the effectiveness of tool use, 1 point was given if the action was correctly achieved whatever the handgrip used, or 0 point if the action was not correctly carried out. Phi coefficient was calculated between grip errors (i.e., non-functional grips) and action errors.

We also assessed the association between the loss of manual dexterity in VF and the type of grip she made (functional/non-functional) for both hands with a chi-square test. We distinguished the tools being grasped with a power grip (bottle opener, hammer, saw, screwdriver) and potentially less impacted by a loss of manual dexterity from the tools being grasped with a precision grip (pen, scissors, key) and potentially more impacted by a loss of manual dexterity.

Additionally, we tested the ability of VF to correctly reach familiar gestures, by measuring the association between the maximum grip size (distance thumb-index) and the

object size at grasped location (in cm) (see Task III; Sirigu et al., 1995). Eight measures (4 for the left hand and 4 for the right hand) were reported for a given tool (among the 16 trials) because we considered only the condition where the tool was presented with the handle toward VF. Correlations were calculated for both hands between object size at grasp location and maximum grip size.

Results. The analysis of variance carried out on percentage of functional grips revealed a main effect of the orientation of the tool, $Q'(1) = 13.76, p < .001$, VF produced more error grips when the tool was presented with the handle away (37.5%) from her than with the handle toward her (76.8%). There was no effect of the hand laterality, $Q'(1) = 2.62, p = .11$, VF did not produce more grip errors with the left hand (48.2%) than with the right hand (66.1%). Finally, the interaction between orientation of the tool and hand laterality showed a trend toward significance, $Q'(1) = 3.25, p = .07$, there was no difference between percentage of functional grip for left (75%) and right hand (78.6%, $p = .74$), whereas VF produced more non-functional grip for the left hand (21.4%) than for the right hand (53.6%, $p < .01$).

Moreover, we did not find any association between grip errors and action errors neither for the left hand ($\phi = -.09, \text{Chi-2} < 1, \text{df} = 1, p = .94$) nor for the right hand ($\phi = -.14, \text{Chi-2} < 1, \text{df} = 1, p = .79$). There were also no association between the grip made by VF (functional or non-functional) and the type of grip associated with a given tool (precision or power grip) neither for the left hand ($\text{Chi-2} = .34, \text{df} = 1, p = .56$) nor for the right hand ($\text{Chi-2} = 0, \text{df} = 1, p = 1$). This last result suggests that the potential loss of dexterity has not influenced the planification of functional grips in VF.

As it can be seen in **Fig.6**, we found significant correlations between the grip aperture (thumb-index distance) and the width of object at grasped location for the left hand ($r = .88, p < .001$) and the right hand ($r = .79, p < .001$) during the grasping to use tools task. There were

no anomalies in the performance of reaching movements in VF. These last results suggested that the grip posture deficit observed in VF cannot result from a basic visuo-motor impairment.

< Insert **Figure 6** about here >

3.2.3 Discussion

VF showed a striking dissociation between grasping to transport versus grasping to use conditions. Whereas she perfectly completed the grasping to transport task, she met severe difficulties in the grasping to use task, which suggests that VF suffers from a specific grasping impairment for familiar tools. In the grasping to use task, VF produced a significant number of non-functional grips when the tool was presented with the handle away from her. Although this deficit seems to be a hallmark of left brain-damage (Sunderland, Wilkins, Dineen, & Dawson, 2013), this behavior tends to be rare and quite mild in LBD patients (2/16 LBD patients produced only 1 uncomfortable posture in Osiurak et al., 2008) and in apraxic LBD patients (3/10 patients produced more than one non-functional grasp in Randerath et al., 2009). Interestingly, in Randerath et al. (2009), only 1 apraxic LBD patient (Patient IL) produced less functional grips than VF when the handle of the tool was presented away (IL: 25% and VF: 37.5%). Moreover, we did not find in the grasping to use task, an association between grip errors and action errors in VF, instead of what we found in our LBD-A group and what it has been previously reported (Randerath et al., 2009). Finally, we ruled out the possibility that the grip deficit observed in VF could be explained by either a perturbation of basic visuo-motor guidance or by a loss of manual dexterity.

In order to stress the association between manipulation knowledge and the presence of the grasping deficit for familiar tools observed in VF, we tested in a third part, different kinds of representations known to support tool use.

3.3. Knowledge supporting tool use

To better understand the deficit presented by VF, we first investigated several forms of knowledge that have been associated with the ability to use tools, that is, functional knowledge, manipulation knowledge, and mechanical knowledge.

3.3.1. Functional matching tasks

The use of tools may rely on semantic memory about their function and context of use (Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000; Osiurak, 2014; Roy & Square, 1985).

Method. VF was asked to select among an array of four pictures the one that best matched the picture of a tool (hammer, jug, electrical plug, match, bottle opener, saw, scissors, screwdriver, key, bulb). In the functional condition, the matching criterion was the function of the tool (e.g., target = match; choice = lighter, pen, coffee maker, colander) and in the contextual condition, the criterion was the usual context of use (e.g., target = match; choice = anniversary, wedding, Christmas day, baptism). There were ten items in each condition. Each correct answer given within 20 s was worth 1 point (maximum score = 10). Cut-off scores were determined as the worst scores achieved by the controls minus two more points for all experimental tasks (Bartolo, Cubelli, Della Sala, & Drei, 2003).

Results. VF obtained 8/10 in the functional matching condition and 9/10 in the contextual matching condition. She performed above the cut-off scores in both conditions (7/10 and 6/10, respectively). VF committed few errors, even if she failed one item (i.e., the saw) in both function and contextual matching tasks. However, VF were able to name all the tools that are presented in this task.

Discussion. VF performed in the normal range for both functional and contextual matching tasks. Consistent with these findings, we found in the preliminary praxis evaluation that VF obtained 10/10 in the functional association task of the TLA (Anicet et al., 2007)

which assesses specifically functional knowledge and we also found in the RTU-C task, that VF made as many selection errors as non apraxic patients, which let us suppose that VF does not suffer from a deficit of selection of tools. Taken together, these results suggest that functional knowledge is relatively spared for this patient.

3.3.2. *Recognition of tool-gesture manipulation*

Using familiar tools may rely upon manipulation knowledge (Buxbaum, 2001; Gonzalez Rothi, Ochipa, & Heilman, 1991). Manipulation knowledge informs individuals about how to manipulate tools (e.g., knowing how to use a hammer is associated with oscillations of the elbow).

Method. This task assessed manipulation knowledge by asking to recognize the best way to hold a tool in order to use it with an object (e.g., saw/piece of wood). The same ten tools as in the semantic about tools task were used. We proposed two versions of this test, that is, the 4-choice Recognition of tool-gesture manipulation (4C-RTM) and the forced-choice Recognition of tool-gesture manipulation (FC-RTM).

The 4C-RTM is one of the classical way to investigate the integrity of manipulation knowledge in patients suffering from apraxia by proposing among several items to select the one that corresponded to the best way to hold a tool (e.g., Jarry et al., 2016). This test was made of the same ten tools used in the functional knowledge tasks. In this test, we proposed four photographs, one with the correct posture and three foils (see Lesourd, Baumard, Jarry, Etcharry-Bouyx, et al., 2017). Each photograph depicted a one-handed manipulation of the tool; the hold differed across photographs, but the relative position of the tools and objects did not vary. The foils were built according three conditions, that is, (1) Active part, the hand is located on the active part of the tool; (2) Uncomfortable hand posture, the hand is oriented on the tool in a way that its subsequent use will be uncomfortable; and (3) Impossible use, the position of the hand on the tool makes impossible its subsequent use. To sum up, there was 4

types of posture: one correct posture (Target), two uncomfortable but possible postures (Active part and Uncomfortable hand posture), and one impossible (Impossible use). There were 10 items, and 1 point was allowed for a correct answer given within 20 s (maximum = 10).

In the 4C-RTM, each posture is not examined independently from each other and one may assume that some subjects select their answer by eliminating the other postures. By presenting only one item at a time in the FC-RTM, we wanted to overcome this potential bias and examined which kind of error is more likely to occur when VF cannot assess several postures simultaneously. The FC-RTM task was computerized using PsychoPy 1.8 (Peirce, 2007) and each 40 photographs (10 tools x 4 conditions) used in the 4C-RTM was presented separately, one at a time on a screen. VF was instructed to recognize if the posture displayed on each picture was correct by pressing “s” on the keyboard or incorrect by pressing “k” on the keyboard. The presentation of the photographs was manually randomized in order to control that two conditions of the same item was not presented two times in a row. Each time VF answered “correct” when a correct posture was presented or “incorrect” when an incorrect posture was presented, 1 point was given (maximum = 10 for each condition). The 4C-RTM and the FC-RTM were completed in this order, in two separate sessions (January 2016 and April 2016, respectively).

In the 4C-RTM, cut-off scores were determined as the worst scores achieved by the controls minus two more points for all experimental tasks (Bartolo, Cubelli, Della Sala, & Drei, 2003), and in the FC-RTM, the presence of a difference between conditions was examined using the non-parametric Cochran’s Q test for binary responses.

Results. In the 4C-RTM, VF made 3 errors (7/10), but her performance was in normal range (cut off score = 6). She failed 3 items (i.e., plug, hammer, bottle opener) that were not the same as those failed in the semantic matching tasks. In the FC-RTM task, the accuracy of

VF to distinguish correct from incorrect postures was 78% (31/40), high above from chance level (binomial $z = 3.32, p < .001$). Furthermore, we found a significant difference between each type of posture accuracy, $Q(3) = 9.32, p < .05$, indicating that the errors made by VF were not distributed uniformly across all the conditions. Whereas VF categorized accurately the Target and Impossible conditions (10/10 and 9/10, respectively), she encountered more difficulties for the Active part condition (7/10) and furthermore for the Uncomfortable hand posture condition (5/10).

Discussion. VF performed in normal range for the 4C-RTM task, suggesting, at first glance, that manipulation knowledge is spared. An account of the gestural deficit of VF (i.e., accurate discrimination of hand postures while impaired execution of hand postures) would be explained by an impaired access to manipulation knowledge (Gonzalez Rothi, Ochipa, & Heilman, 1991; Heilman, Rothi, & Valenstein, 1982). However, when examining the results obtained in the FC-RTM task, we found that VF was able to classify without difficulties correct and impossible postures but encountered more difficulties for more ambiguous hand postures (i.e., uncomfortable hand postures). In the case of familiar objects, most apraxic patients are impaired in gesture recognition as well as in gesture production, indicating damage to the representation underlying knowledge of appropriate hand postures for functional object interactions (Buxbaum et al., 2003).

3.3.3. Mechanical Problem-solving task.

The interaction between the tool and the object may depend on mechanical knowledge (Goldenberg & Hagmann, 1998; Jarry et al., 2013; Osiurak, Jarry, & Le Gall, 2010). Mechanical knowledge can be assessed using mechanical problem-solving tasks in which patients have to select and use tools for which there is no pre-existing usage (e.g., choosing a tool to lever a cylinder; Goldenberg & Hagmann, 1998).

Method. VF was presented successively with three mechanical problem-solving tasks previously described in Lesourd et al. (2016). In the choice condition (MPS-C), she was instructed to extract a red wooden target out from a transparent box, using her both hands and one or more tools to be selected among eight rods offering different mechanical properties (e.g., long/short, rigid/bendable). In the no-choice condition (MPS-NC), only one relevant tool was proposed to VF with each box. The time limit was set to 3 minutes per item and performance was scored on a 3-point scale: (3) The target is extracted from the box; (2) The first step of the problem is completed; (1) The target has been reached with a rod but the first step is not completed; (0) The participant does not reach the target. The maximum total score was 9 (i.e., 3 problems x 3 points). Additionally, in the choice condition, we also assessed the strategy used by VF by recording the time spent in 4 conditions: (1) Interacting the tool with the box (Tool-box); (2) Manipulating the tool in isolation (Tool), (3) Manipulating the box in isolation (Box); and (4) No action (No action). This procedure has been previously used (Lesourd et al., 2016; Osiurak, Jarry, Lesourd, Baumard, & Le Gall, 2013) and results showed distinct pattern of time spent in each condition between brain damaged patients and controls.

Results. For both MPS-C and MPS-NC, VF performed in normal range (MPS-C: 7/9, cut-off score: 7/9 and MPS-NC: 8/9, cut-off score: 7/9). Moreover, in the MPS-C, we found the same pattern of time spent in each condition between VF and Controls: Tool-box (VF: $M = 54\%$, Controls: $M = 43\%$, $SD = 11$; modified- $t = .91$, $p = .21$), Tool (VF: $M = 26\%$, Controls: $M = 24\%$, $SD = 13$; modified- $t = .14$, $p = .45$), Box (VF: $M = 12\%$, Controls: $M = 21\%$, $SD = 13$; modified- $t = -.63$, $p = .28$) and No action (VF: $M = 9\%$, Controls: $M = 11\%$, $SD = 7$; modified- $t = -.26$, $p = .40$). Moreover, the mean completion time did not differ between VF and controls (VF: $M = 96s$, Controls: $M = 49s$, $SD = 47$, modified- $t = .91$, $p = .21$). Finally, VF grasped a similar number of tools compared to Controls during the task (VF: $M = 2.67$, Controls: $M = 2$, $SD = 1.21$, modified- $t = .51$, $p = .32$), importantly, she did not

grasp more irrelevant tools compared to controls (VF: $M = 0$, Controls: $M = .25$, $SD = .45$, modified- $t = -.51$, $p = .32$).

Discussion. VF performed normally in both MPS-C and MPS-NC tasks, which suggests that VF understood the mechanical interactions needed to solve the task. Moreover, she showed the same pattern of strategy compared to controls (i.e., more time spent in the Tool-box condition), which is interesting given that previous studies found that apraxic patients failed this kind of task (Goldenberg & Hagmann, 1998; Jarry et al., 2013) and showed a particular pattern of strategy (i.e., same amount of time spent in each condition; Osiurak et al., 2013). Mechanical knowledge, a crucial form of representation supporting tool use, seems to be spared in VF.

3. General discussion

In the present study, we reported the case of VF, a left-handed patient, who presented a severe apraxia following a cerebrovascular accident involving a wide part of her right hemisphere. One of the main findings is that VF who presented a high frequency of hand posture errors does not show a severe deficit of manipulation knowledge. Thus, the deficit of hand posture observed in VF may not be caused by impaired manipulation knowledge. Here we found that VF produced a significant number of hand posture errors even with the tool in hand, instead of LBD apraxic patients who significantly improved their performance with the tool in hand (i.e., single tool use and real tool use tasks). Thus, the predictions of the MBA seem to be limited to the pantomime of tool use task, as the presence of hand posture errors are atypical once the tool has been grasped (Osiurak, Aubin, Allain, Jarry, Etcharry-Bouyx, et al., 2008; Randerath et al., 2009), except for some rare cases described in the literature (e.g., patient LL; Sirigu et al., 1995). Regarding the status of manipulation knowledge in VF, if we assume that the presence of hand posture errors is the hallmark of impaired manipulation knowledge according to the MBA, we found that VF was still able to use familiar tools with

their corresponding objects. This is another limit for this approach as it questions the role and the importance of manipulation knowledge to explain tool use situations and particularly real tool use situations which are the most frequent in everyday life.

As mentioned just above, another finding of the present study was the presence of a dissociation between high frequency of hand posture errors and few action errors in VF. In line with the RBA that hypothesizes that mechanical knowledge is essential to use familiar and novel tools (Osiurak & Badets, 2016; Osiurak et al., 2010, 2011), we found that VF had spared mechanical knowledge. Additionally, the RBA posits that in a situation where a tool has to be used with an object, the technical reasoning process generates a mental simulation of how the tool has to be used with an object (i.e., expected perceptual effect) and is followed by a simulation of the potential motor actions (i.e., motor simulation) which evaluate the costs associated with the intended tool-use actions. It is therefore possible that VF cannot adapt the mental simulation via motor simulation to the situation of tool use and would explain why VF produced a significant number of hand posture errors in absence of action errors. Thus, a dissociation between the mental simulation originating from technical reasoning process and motor simulation is a good candidate to explain the deficit observed here but further studies are needed to test this hypothesis.

So far, we have not discussed the pattern of performance (i.e., behavioral and cognitive) observed in VF in association with the side of the lesion. If the extent of the lesion did not allow to make specific neurocognitive hypotheses, we can still discuss the potential involvement of the right hemisphere in supporting praxis functions. Indeed, the patient is left-lateralized for language functions and showed a severe apraxia following a right-brain lesion, which is atypical. To better understand the role of the right hemisphere, we proposed three potential brain organization in the introduction, that we will now discuss in turn.

First, we considered a co-dominance of the left hemisphere for praxis and language functions in VF. There is now strong evidence for co-occurrence of language and praxis lateralization, whatever the handedness (Vingerhoets et al., 2012, 2013). Moreover, according to the MBA, impaired manipulation knowledge is more likely to occur following a left-brain lesion rather than a right-brain lesion (Buxbaum, 2001; see also Buxbaum, Shapiro, & Coslett, 2014). VF is left-lateralized for language, thus suggesting that praxis functions may also be left-lateralized. In line with this hypothesis, we found that mechanical and functional knowledge were spared in VF. However, the sub-normal results in recognition of tool-gesture manipulation task and the high frequency of hand posture errors both suggested that manipulation knowledge was not completely spared. In broad terms, it is unlikely that manipulation knowledge relies only upon the left hemisphere. This cerebral organization does not seem to apply to VF.

Second, we considered a left-lateralization for language and a right-lateralization of praxis functions in VF. Only two cases of left-handed apraxic patients following right-brain lesions have been described in the literature. Margolin (1980) described the case of a left-handed patient without aphasia suffering from apraxia and agraphia following a large right hemisphere infarct. Ochipa and colleagues (1989) reported a similar case of a left-handed patient who showed a deficit of manipulation knowledge⁴ following a right-brain infarct. In a fMRI study on left-handed healthy subjects (Króliczak et al., 2011), only 7% of participants ($n = 1/15$; Subject 5) showed a left-lateralization for language and a right-lateralization for praxis, confirming the rareness of this cerebral organization for praxis and language functions.

⁴ At the time, Ochipa and colleagues (1989) interpreted the deficit of their patient in terms of “a loss of knowledge related to tool use”, which refers to the current concept of manipulation knowledge.

In line with this cerebral organization, VF did not present any evidence of aphasia in the neuropsychological evaluation and brain activations were mainly observed in the left hemisphere during denomination tasks. Furthermore, VF presented important signs of apraxia (e.g., pantomime of tool use, imitation of gestures, hand posture errors during tool use, etc.) following right-brain lesion, leading us to suggest that control mechanisms for language and praxis functions could be anatomically and functionally distinct. However, if the praxis system was right-lateralized in VF, then functional knowledge and mechanical knowledge would have been both impaired, but this not what we found, making this proposal unlikely.

Third, we considered a left-lateralization of language and a bilateral organization of praxis functions in VF. In the aforementioned work of Króliczak and colleagues (2011), one left-handed subject (i.e., Subject 4) showed a left-lateralization for language and a bilateral organization of praxis functions. Moreover, if several fMRI meta-analyses have stressed the left-lateralization of the representations supporting tool use, they also have acknowledged the presence of significant activation in bilateral pMTG (Ishibashi et al., 2016; Lewis, 2006; Reynaud et al., 2016), a brain structure associated to the ability to retrieve and identify the correct object-related gesture (Kalénine, Buxbaum, & Coslett, 2010) and to produce postural aspects of tool-related actions (Buxbaum et al., 2014). This suggests that right pMTG may also represent, at least in part, some aspects of manipulation knowledge. In VF, assuming a bilateral organization of praxis functions, all the representations supporting tool use should have been impacted following a right brain lesion. This is what we observed with manipulation knowledge but not with functional and mechanical knowledge, which were both preserved. An alternative account of bilateral organization is to postulate that praxis functions are fractionated and could be distributed distinctively across both hemispheres. In the present case, manipulation knowledge may rely upon both hemispheres, whereas mechanical and functional knowledge may be both relying upon the left hemisphere. Thus, the latter proposal

well explained the pattern of results observed in VF. However, considering a bilateral representation of manipulation knowledge, there is still a discrepancy between the moderate level of impairment of manipulation knowledge and the high frequency of hand posture errors. Moreover, because her contralateral left hemisphere should contribute to the neural substrate of manipulation knowledge, VF should present less hand posture errors compared to LBD apraxic patients in single and real tool use tasks, but this was not the case. In addition to that, in the grasping to use task, VF produced more non-functional grips compared to the results from the literature in both LBD and RBD patients (Osiurak, Aubin, Allain, Jarry, Etcharry-Bouyx, et al., 2008; Randerath et al., 2009).

According to the rareness of the observation reported here, one may assume that VF is not apraxic but suffers from optic ataxia, given that the differential diagnosis between optic ataxia and apraxia is sometimes difficult. Optic ataxia has been interpreted as an impairment of real-time automatic adjustments (Rossetti, Pisella, & McIntosh, 2017; Rossetti, Pisella, & Vighetto, 2003) following lesions in the superior parietal lobe (BA7) and precuneus. Patients with optic ataxia can exhibit grasping deficits in that they demonstrate poorly scaled grip aperture, yet grasping can be selectively impaired (Jeannerod, Decety, & Michel, 1994). However, we showed that VF did not suffer from a performance of basic visuomotor guidance, her movements were smooth, and she was able to perfectly scale her grip aperture in accordance with the size of objects she had to grasp. VF had a large brain lesion, but the anatomical data showed that the SPL (BA5/7) was spared in both hemispheres. Moreover, VF showed a deficit for shaping her hand while using familiar tools, as it has been previously observed in the patient LL (Sirigu et al., 1995). At the time, Sirigu et al. (1995) argued in favor of the existence of a central store for manual postures, which was the starting point of the MBA (Buxbaum, 2001), for whom, a deficit of hand posture was a hallmark of ideomotor apraxia. VF was also strongly impaired when she had to produce pantomime of tool use on

visual presentation of the tool, a task traditionally used to assess the presence of apraxia (Goldenberg, 2009). Thus, we can rule out the possibility that VF suffered from optic ataxia and we can even conclude that VF was presenting apraxia, with the inability to correctly shape her hand for grasping familiar tools.

Another interesting question concerns the potential association between the loss of manual dexterity of the left hand and the deficit of hand posture. One may assume that the production of incorrect hand postures by VF could be explained by a loss of manual dexterity. For instance, in the grasping to use task, the patient produces more non-functional grips with the left hand, even if there was only a trend to significance for the interaction between type of grip and hand laterality. However, we did not find any association for both hands between the grip produced by VF (functional vs non-functional) and the grip associated with a given tool (power vs precision). Thus, the loss of manual dexterity cannot explain on its own the number of non-functional grips made by VF. Furthermore, we found that the deficit of hand posture was observed only for familiar tools, whereas a loss of dexterity would have impacted also novel tools (i.e., grasp to transport and mechanical problem-solving tasks). Finally, if VF produced hand posture errors, she did not commit action errors. Nevertheless, one may stipulate that a loss of dexterity should impact the real use of tools and may have caused action errors. For instance, in corticobasal degeneration, a pathology associated with a loss of manual dexterity to the contralateral hand to the brain lesion (Litvan et al., 1999), patients are impaired for using both familiar and novel tools (Baumard et al., 2016). Thus, the loss of manual dexterity seems to play, at best, a minor role on the deficit of hand postures reported in the present case.

4. Conclusion

In the present work, we reported the atypical case of a left-handed patient, left-lateralized for language, who showed a severe apraxia following a right-brain lesion (see also

Margolin, 1980). Interestingly, the performance of VF called for a striking dissociation between tool-hand representations and tool-object representations. Our investigation pointed out the limits of the MBA by questioning the link between manipulation knowledge and (1) hand posture; (2) situations of real tool use. Our investigation also revealed that VF was probably neither left-lateralized nor right-lateralized for praxis functions but nevertheless showed evidence for a bilateral organization. In fact, irrespective of the possible cerebral lateralization of praxis functions examined in VF, none of them was satisfactory to explain the association between manipulation knowledge and hand posture errors. Finally, we found that the RBA was an interesting alternative account to explain VF's performance, but further studies are needed to confirm his predictions.

Additional information

We confirmed that no part of the study procedures or analyses were pre-registered prior to the research being conducted.

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Figures

Figure 1. Manual prehension of a pair of scissors by VF who was asked to cut the piece of paper with the scissors (real tool use). The first three frames (a.-d.) show the behavior of VF during attempts at manipulating the tool and making interact the tool with the object. In the last two frames (d. and e.), VF correctly achieved the action (i.e., cutting the piece of paper) using an incorrect hand posture (i.e., hand posture error).

Figure 2. On the left panel: T1-weighted axial slices of VF brain performed at the chronic stage of stroke (6 months after the stroke). On the right panel: Lesion extension (red color) was determined using the Marina (MAKs for Region of INterest Analysis; Walter et al., 2003) atlas on the basis of a T1-weighted sequence and projected on a MNI template using MRIcroGL (<https://www.mccauslandcenter.sc.edu/mricrogl/>). Several probabilistic brain regions involved in tool use skills were projected on the MNI template: SPL (BA5/7; Scheperjans, Eickhoff, et al., 2008; Scheperjans, Hermann, et al., 2008), IPS (Scheperjans, Hermann, et al., 2008), IPL (AG and SMG; Caspers et al., 2006), IFG (BA44/45; Amunts et al., 2004) were selected from the Anatomy toolbox (Eickhoff et al., 2005) and pMTG were selected from the AICHA atlas (Joliot et al., 2015). Spared brain areas are colored in green whereas damaged brain areas are colored in yellow. SPL: Superior Parietal Lobe; IPS: Intraparietal Sulcus; AG: Angular Gyrus; SMG: Supramarginal Gyrus; IFG: Inferior Frontal Gyrus; pMTG: posterior Middle Temporal Gyrus.

Figure 3. Scores of VF, LBD-A, LBD-NA and RBD patients on the hand posture, arm posture, amplitude and timing components during pantomime of tool use task (left panel) and single tool use task (right panel). The boxplots display the interquartile range (first quartile, median, third quartile). For the sake of clarity, we reported only statistical comparisons between VF and LBD-A patients for hand posture component. * $p < .05$

Figure 4. Scores of VF, LBD-A, LBD-NA and RBD patients for action accuracy (left panel) and hand posture accuracy (right panel) in the real tool use task in choice condition (RTU-C). The boxplots display the interquartile range (first quartile, median, third quartile). For the sake of clarity, we reported only statistical comparisons between VF and all three groups of patients. ns: non-significant, *** $p < .001$, ° $p = .08$.

Figure 5. Apparatus used in the grasping to transport (A.) and in the grasping to use task (B.). Left hand and right hands were assessed in both tasks (only initial position of the right hand is showed here). In the gasping to use task, the handle of the tool can be presented either toward (B1.) or away (B2.) from the patient. In this example, if VF can grasp the hammer either with the thumb away from the active part of the tool (non-functional grip) or with the thumb toward the active part (functional grip).

Figure 6. Scatter plot for maximum grasp size (thumb-index distance) as a function of the width of the object at grasped location for the left hand and the right hand. Each color represents a specific tool.

Fig.1

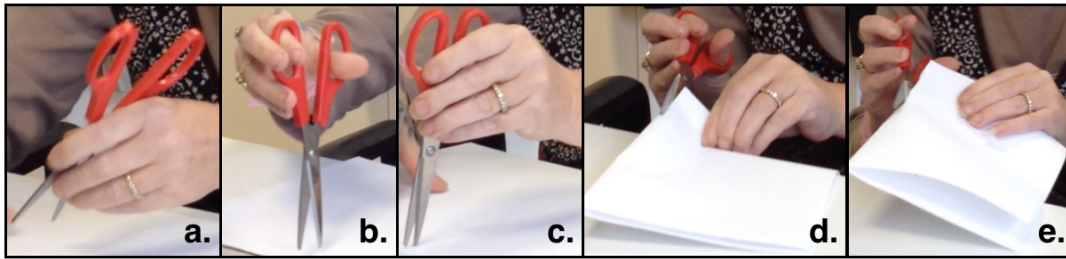


Fig.2

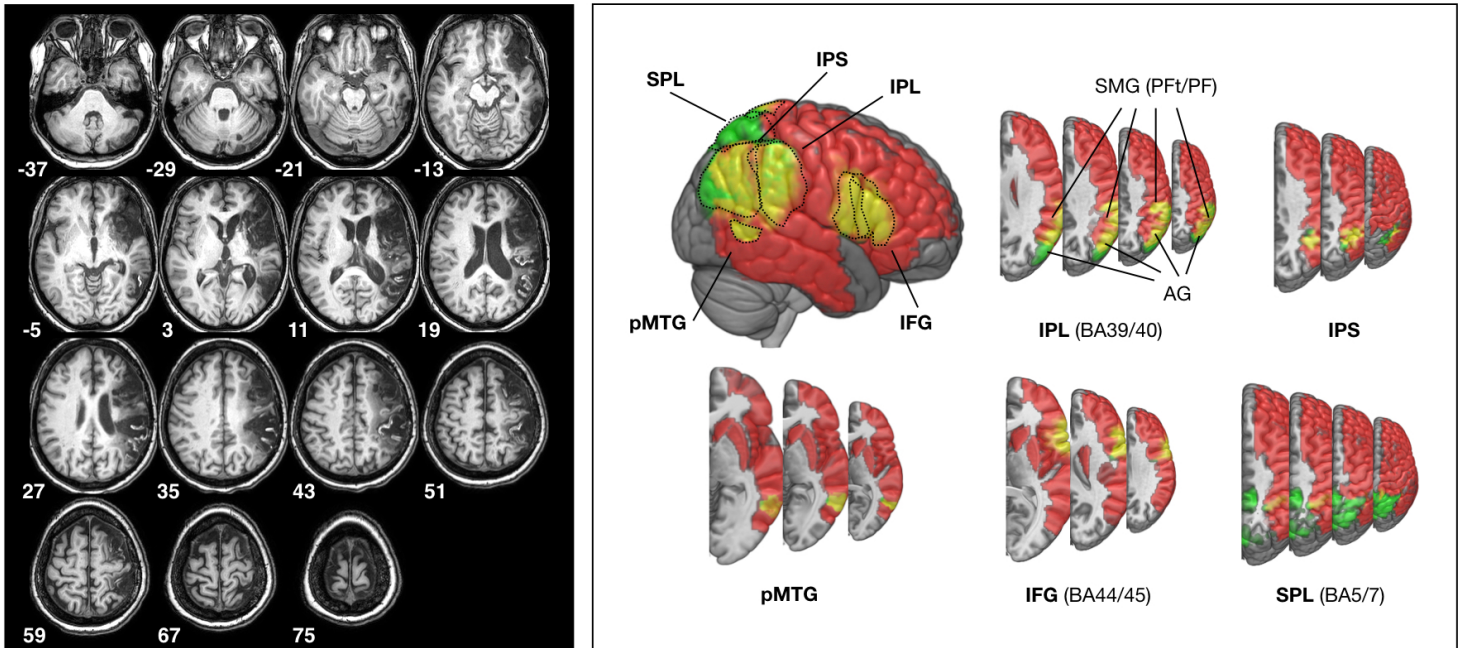


Fig.3

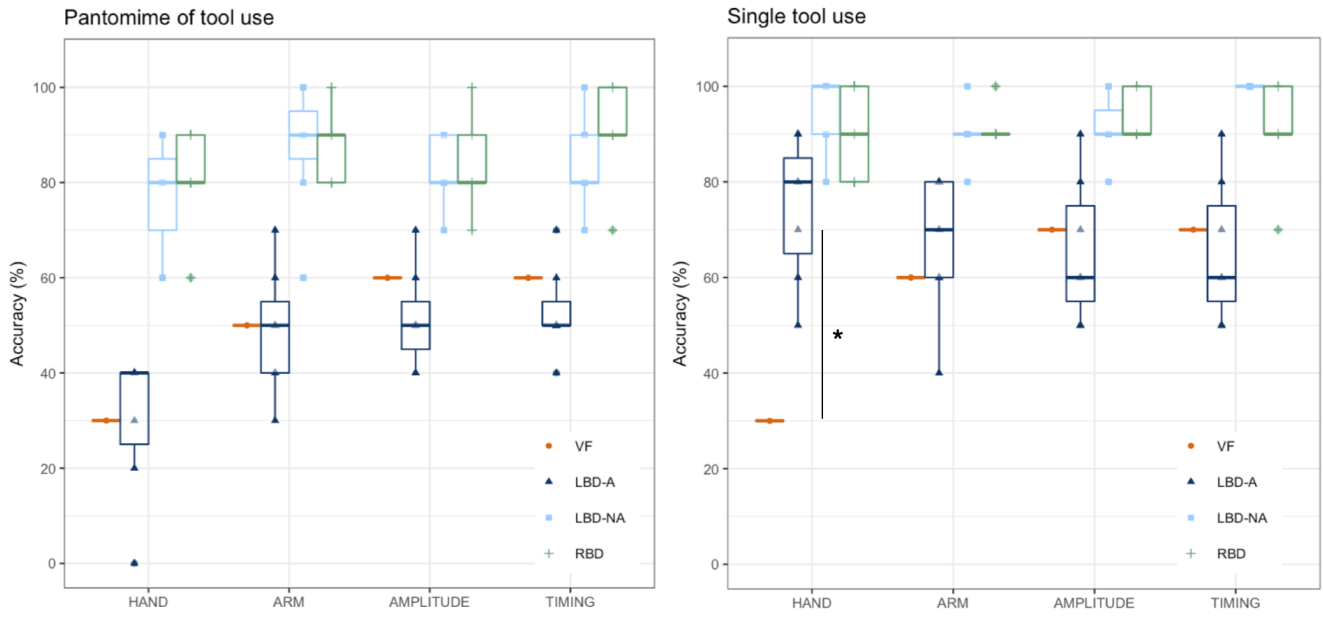


Fig.4

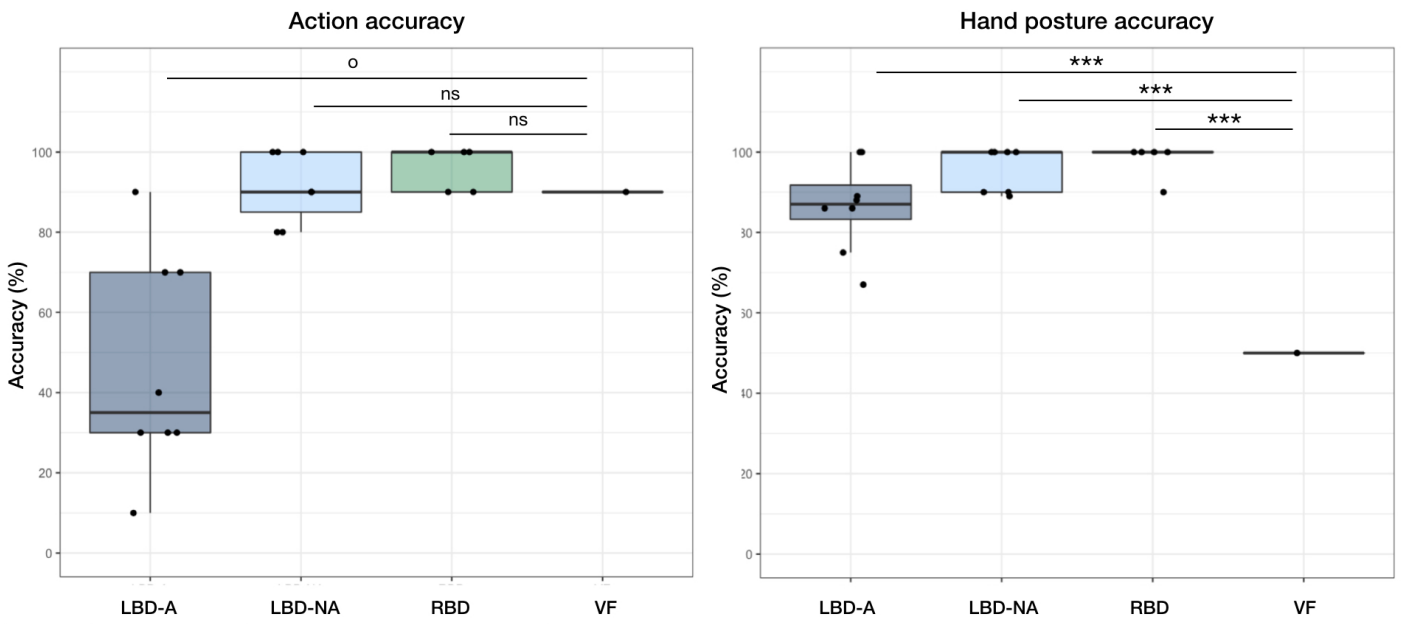


Fig.5

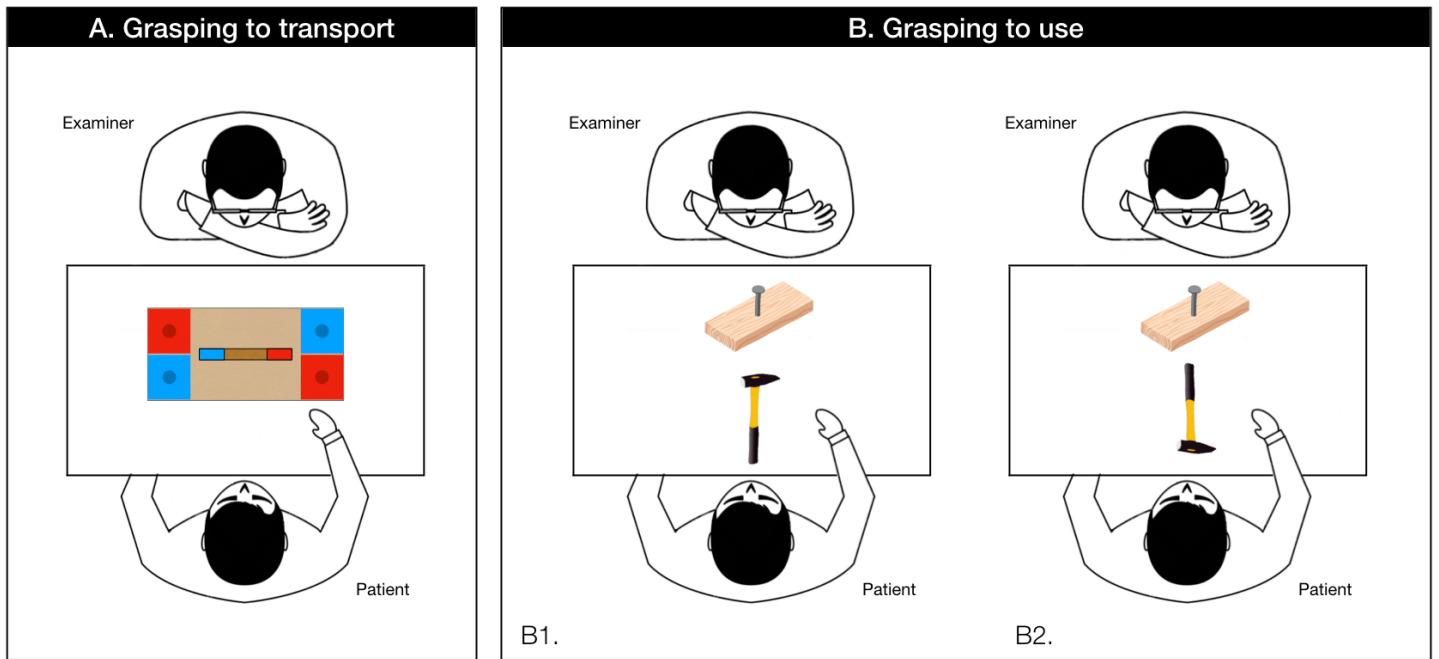
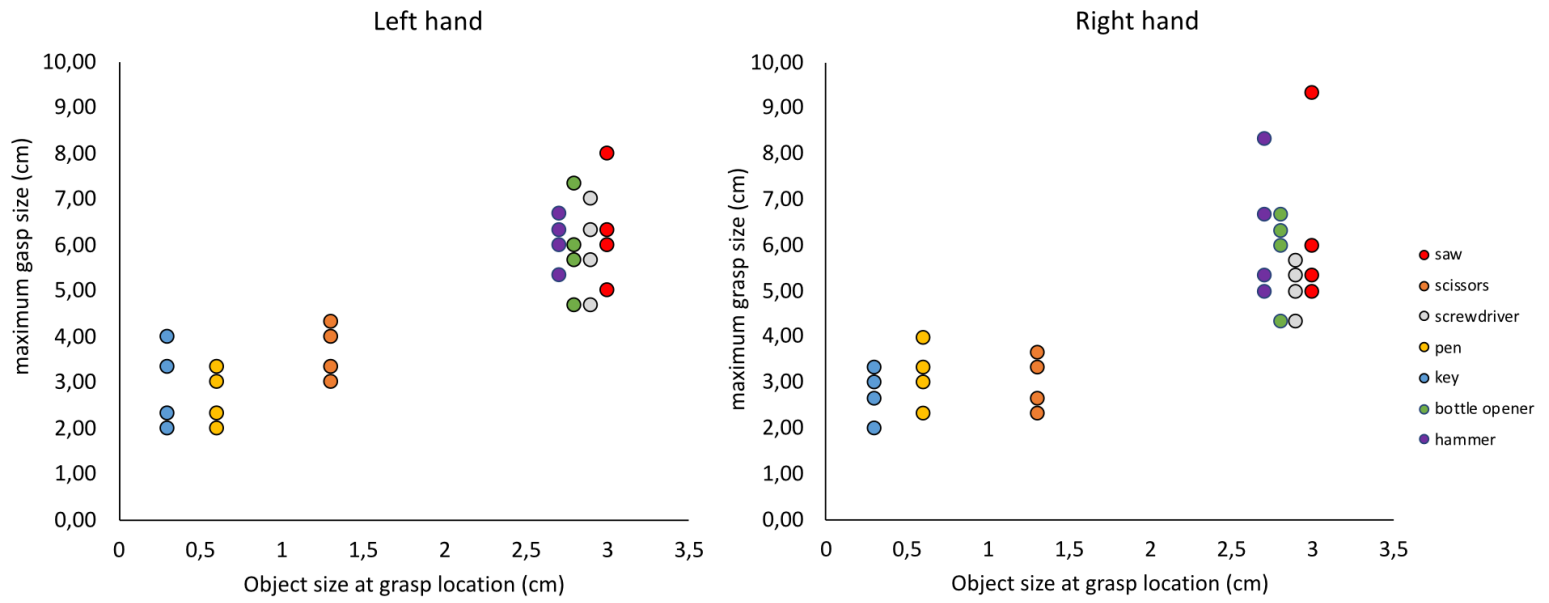


Fig.6



Tool use and hand posture

Table 1. Preliminary neuropsychological assessment

| Functions/Tests | Raw score | z score or percentile |
|--|-------------------|-----------------------|
| <i>Global functioning</i> | | |
| MMSE | 23/30 | |
| Verbal intelligence (fNART) | 86 | P16 |
| Perceptual Reasoning Index (WAIS IV) | 76 | P5 |
| Matrix subtest | 11/19 | ss = 7 |
| Puzzles subtest | 6/19 | ss = 5 |
| <i>Long term memory</i> | | |
| Californiva Verbal Learning Test | | |
| Total Free Recall List A | 43/80 | z = -1.09 |
| Total Recall List A after interference | 7/16 | z = -1.94 |
| Total Recall List A after delay | 7/16 | z = -2.24 |
| Recognition | 10/16 | z = -2.73 |
| Doors test | | |
| Part A | 12/12 | P75-99 |
| Part B | 9/12 | P75-99 |
| <i>Working memory and short term memory</i> | | |
| Forward auditory digit span (WAIS IV) | 5 | ss = 8 |
| Backward auditory digit span (WAIS IV) | 4 | ss = 7 |
| Corsi forward visuospatial span | 5 | z = -.54 |
| Corsi backward visuospatial span | 3 | z = -1.31 |
| <i>Executive functioning</i> | | |
| TMT (B-A) | 143 | z = -2.83 |
| Wisconsin Card Sorting Test (categories) | 6/6 | P25-99 |
| Brixton (errors) | 25 | <P5 |
| Hanoi tower (errors) | 34 | z = -3.53 |
| <i>Visuo-spatial/Visuoconstructive functions</i> | | |
| Incomplete letters (VOSP) | 20/20 | 17 ^a |
| Bells test (Omissions Left-Right) | 3 | <P5 |
| Cube analysis (VOSP) | 7/10 | 6 ^a |
| Taylor Complex Figure copying | 26/36 | -2.55 |
| <i>Language</i> | | |
| Token test | 163/164 | >P70 |
| Fluency (P) | 14 | z = -.86 |
| Fluency (Animals) | 21 | z = -.91 |
| <i>Motricity</i> | | |
| Dynamometer (3 trials/hand) (Kg) | | |
| Left hand | 10 | z = -3.14 |
| Right hand | 12 | z = -2.99 |
| Purdue pegboard | | |
| Left hand | 9 | z = -4.76 |
| Right hand | 13,3 | z = -1.28 |
| Motor sequence (fist-edge-palm test) | impossible | |

Pathological scores are in bold

MMSE: Mini-mental state examination; fNART: french National Adult Reading; WAIS IV: Wechsler Adult Intelligence Scale 4th version; TMT: Trail Making Test VOSP: Visual Object and Space Perception; z: z score; ss: WAIS IV scaled score; P: Percentile;

^a Cut-of score

Table 2. Preliminary praxis testing: TLA (Anicet et al., 2007)

| | Raw score | Significance |
|--|--------------|--------------|
| <i>Intransitive and meaningless gestures</i> | | |
| <i>Imitation of meaningless gestures</i> | | |
| Hand postures | 6/10 | *** |
| Finger postures | 9/10 | * |
| <i>Symbolic gestures</i> | | |
| Naming | 20/20 | |
| Production on verbal command | 12/20 | *** |
| Imitation | 12/20 | *** |
| <i>Discrimination of gestures according to their meaning</i> | 15/20 | n.s. |
| <i>Transitive gestures</i> | | |
| <i>Semantic knowledge about tool use</i> | | |
| Functional matching | 10/10 | |
| <i>Pantomime of tool use</i> | | |
| Production on verbal command | 9/20 | *** |
| Imitation | 9/20 | *** |
| <i>Object use</i> | 11/20 | *** |

Pathological scores are in bold

TLA: Test Lillois d'Apraxie gestuelle (french battery for apraxia screening)

* $p < .05$, ** $p < .01$, *** $p < .001$

Tool use and hand posture

Table 3. Demographics and clinical data of patients and controls included in this study

| Subject | Group | Handedness | Gender | Age (years) | Education | Onset (days) | Lesions |
|-----------|---------|------------|--------|----------------|------------|-----------------|--------------|
| VF | | L | Female | 49 | 9 | 450 | F,P,T, I, BG |
| C1 | Control | R | Female | 50 | 9 | | |
| C2 | Control | L | Female | 54 | 12 | | |
| C3 | Control | R | Female | 56 | 12 | | |
| C4 | Control | R | Female | 54 | 9 | | |
| C5 | Control | R | Female | 52 | 12 | | |
| Mean (SD) | | | | 52.5 (2.7) | 10.5 (1.6) | | |
| P1 | LBD-A | R | Male | 63 | 12 | 10 | F,T,P,BG |
| P2 | LBD-A | R | Male | 71 | 7 | 17 | P |
| P3 | LBD-A | R | Female | 82 | 7 | 17 | BG |
| P4 | LBD-A | R | Female | 69 | 17 | 18 | F |
| P5 | LBD-A | R | Female | 84 | 7 | 16 | F,T,P,BG |
| P6 | LBD-A | R | Female | 62 | 12 | 21 | T,P |
| P7 | LBD-A | R | Female | 81 | 5 | 11 | T,O |
| P8 | LBD-A | R | Female | 70 | 7 | 12 | F,P |
| Mean (SD) | | | | 72.8 (8.6) | 9.3 (4.0) | 15.3 (3.8) | |
| P9 | LBD-NA | R | Female | 76 | 7 | 12 | T,P,BG |
| P10 | LBD-NA | R | Female | 71 | 12 | 11 | F,P |
| P11 | LBD-NA | R | Male | 62 | 20 | 10 | T,O |
| P12 | LBD-NA | R | Male | 49 | 11 | 14 | F,T,P,BG |
| P13 | LBD-NA | R | Male | 53 | 14 | 9 | P |
| P14 | LBD-NA | R | Male | 76 | 17 | 14 | P,BG |
| P15 | LBD-NA | R | Male | 77 | 10 | 5 | F,P |
| Mean (SD) | | | | 66.3 (11.7) | 13.0 (4.4) | 10.7 (3.1) | |
| P16 | RBD | R | Female | 74 | n.a. | 50 | T |
| P17 | RBD | R | Male | 44 | 11 | 26 | F,T |
| P18 | RBD | R | Male | 70 | 11 | 30 | BG |
| P19 | RBD | R | Female | 41 | 11 | 106 | F,T |
| P20 | RBD | R | Male | 65 | 17 | 33 | F |
| Mean (SD) | | | | 58.8 (15.3) | 12.5 (3.0) | 49.0 (33.2) | |

LBD-A: Left Brain-Damaged Apraxic; LBD-NA: Left Brain-Damaged Non Apraxic; RBD: Right Brain Damaged; R: Right; L: Left; F: Frontal; T: Temporal; P: Parietal; I: Insula; BG: Basal Ganglia; PTU: Pantomime of Tool Use; STU: Single Tool Use; n.a.: not available