*Journal of the International Neuropsychological Society* (2017), **23**, 128–138.
Copyright © INS. Published by Cambridge University Press, 2017.
doi:10.1017/S1355617716000618

# Rethinking the Cognitive Mechanisms Underlying Pantomime of Tool Use: Evidence from Alzheimer's Disease and Semantic Dementia

Mathieu Lesourd,[1,2] Josselin Baumard,[3,4] Christophe Jarry,[3,4] Frédérique Etcharry-Bouyx,[3,4] Serge Belliard,[5,6] Olivier Moreaud,[7,8] Bernard Croisile,[2] Valérie Chauviré,[9] Marine Granjon,[1] Didier Le Gall,[3,4] AND François Osiurak[1,10]

[1]Laboratoire d'Etude des Mécanismes Cognitifs (EA 3082), Université de Lyon, France
[2]Service de Neuropsychologie, Hôpital Neurologique Pierre Wertheimer, Bron, France
[3]Laboratoire de Psychologie des Pays de la Loire (EA4638), Université d'Angers, France
[4]Unité de Neuropsychologie, Département de Neurologie, Centre Hospitalier Universitaire d'Angers, France
[5]Service de Neurologie, Centre Hospitalier Universitaire, Rennes, France
[6]Laboratoire de Neuropsychologie, Unité INSERM U 1077, Caen, France
[7]CMRR Grenoble Arc Alpin, Pôle de Psychiatrie et Neurologie, Centre Hospitalier Universitaire de Grenoble, France
[8]Laboratoire de Psychologie et Neurocognition CNRS UMR 5105, Grenoble, France
[9]Département de Neurologie, Centre Hospitalier Universitaire d'Angers, France
[10]InstitutUniversitaire de France, Paris, France

(RECEIVED April 7, 2016; FINAL REVISION June 22, 2016; ACCEPTED June 26, 2016)

## Abstract

**Objectives:** Pantomiming the use of familiar tools is a central test in the assessment of apraxia. However, surprisingly, the nature of the underlying cognitive mechanisms remains an unresolved issue. The aim of this study is to shed a new light on this issue by exploring the role of functional, mechanical, and manipulation knowledge in patients with Alzheimer's disease and semantic dementia and apraxia of tool use. **Methods:** We performed multiple regression analyses with the global performance and the nature of errors (i.e., production and conception) made during a pantomime of tool use task in patients and control participants as dependent variables and tasks investigating functional, mechanical, and manipulation knowledge as predictors. **Results:** We found that mechanical problem solving, assessing mechanical knowledge, was a good predictor of the global performance of pantomime of tool use. We also found that occurrence of conception errors was robustly predicted by the task assessing functional knowledge whereas that of production errors was not explained by only one predictor. **Conclusions:** Our results suggest that both functional and mechanical knowledge are important to pantomime the use of tools. To our knowledge, this is the first demonstration that mechanical knowledge plays a role in pantomime of tool use. Although impairment in pantomime of tool use tasks (i.e., apraxia) is widely explained by the disruption of manipulation knowledge, we propose that pantomime of tool use is a complex problem-solving task. (*JINS*, 2017, *23*, 128–138)

**Keywords:** Apraxia, Alzheimer's disease, Semantic dementia, Manipulation knowledge, Mechanical knowledge, Functional knowledge, Pantomime of tool use

## INTRODUCTION

Pantomiming the use of familiar tools on visual presentation is a central test in the assessment of apraxia (Goldenberg, Hartmann, & Schlott, 2003; Vingerhoets, Vandekerckhove, Honoré, Vandemaele, & Achten, 2011). In this test, participants are asked to show how they would use a tool without holding it in hand. However, this task is thought to be more difficult than single tool use (i.e., participants are asked to grasp a tool and to demonstrate the movement involved in its typical use) or real tool use (i.e., participants are asked to do what is typically done with a tool and the associated object), notably because the underlying cognitive mechanisms remain unsolved (Bartolo & Cubelli, 2014) and are still under debate (e.g., Osiurak, Jarry, & Le Gall, 2011).

Overall, three types of knowledge have been proposed to account for performance in pantomime of tool use

---

Correspondence and reprint requests to: Mathieu Lesourd, Laboratoired'Etude des MécanismesCognitifs (EA 3082), Institut de Psychologie, 5, avenue Pierre Mendès-France, 69676 BronCedex, France. E-mail: mathieu.lesourd@chu-lyon.fr

(PTU): functional knowledge (Goldenberg, 2013; Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000), manipulation knowledge (Buxbaum, 2001; Rothi, Ochipa, & Heilman, 1991) and mechanical knowledge (Goldenberg & Hagmann, 1998; Jarry et al., 2013; Osiurak et al., 2009). The aim of this study is to assess the ability of each of these three kinds of knowledge to predict the global performance and the nature of errors in the PTU task in Alzheimer's disease (AD) and semantic dementia (SD). Indeed, the study of AD and SD is a good way to investigate the role of manipulation, functional, and mechanical knowledge in the PTU task.

In the field of apraxia, defects in pantomime production can be observed in case of deficits in semantic knowledge about tool function (i.e., functional knowledge; Ochipa, Rothi, & Heilman, 1989). Functional knowledge contains information about canonical relationships between tools and objects. In that case, patients exhibit content errors (i.e., the patient does not perform the expected gesture; Ochipa et al., 1989) or perplexity (i.e., the patient does not produce any gestures at the sight of a tool or gives unmistakable sign of not knowing what to do with the tool; Poeck, 1983). These errors occur when functional knowledge is lost, thereby suggesting that functional knowledge is at least necessary to pantomime the use of tools. To correctly perform pantomimes of tools, participants would have to activate object representations from semantic memory before virtually using these represented tool and object together (e.g., to pantomime the use of a hammer, it is necessary to be able to imagine the hammer in the hand but also a nail in a wooden board) (Goldenberg et al., 2003). In sum, when pantomiming the use of a tool, the occurrence of conception (content and perplexity) errors suggests that semantic representations about tool function could be impaired.

While functional knowledge has been proposed to be involved in pantomiming the use of tool, activation of manipulation knowledge has been proposed to be a prerequisite to perform pantomime actions (i.e., manipulation-based approach; Rothi et al., 1991). This type of knowledge informs individuals 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. In a clinical setting, an impairment of manipulation knowledge may lead to different kinds of errors in the production of the gesture like spatiotemporal errors (e.g., one or more incorrect features of the gesture to produce), or "body-part as object" errors (i.e., a part of the body is used as the target tool) (Buxbaum, 2001).

In recent years, some authors have argued that the ability to pantomime the use of a tool can be explained without invoking activation of manipulation knowledge (Goldenberg, 2013). Indeed, mechanical knowledge may be necessary to create a representation of the action, as is the case for any situation involving tool use (Osiurak et al., 2011). Moreover, Goldenberg (2013) argued that pantomime of tool use cannot be reduced to the activation of motor programs[1] of real tool use; and that manipulation knowledge can be actually replaced by combining functional knowledge with mechanical problem-solving skills. In this view, producing a pantomime is a problem-solving task and pantomimes can be considered as novel gestures because no motor program is available in long-term memory (Bartolo & Cubelli, 2014). For instance, when a participant is asked to demonstrate the use of a hammer, the localization and orientation of the imagined nail relative to the body may lead to different motor programs across participants (e.g., hammering with a vertical *vs.* a horizontal motion).

To sum up, at least three types of knowledge seem to be involved in pantomime of tool use (i.e., manipulation knowledge, functional knowledge, and mechanical knowledge), but their exact role is still an open issue. In this study, we explore the ability of functional, manipulation, and mechanical knowledge to predict not only the global performance but also the nature of errors in the PTU task in AD and SD. It has been shown that manipulation, functional, and mechanical knowledge are all impaired in AD (for a review, see Lesourd et al., 2013a, 2013b). Concerning SD, mechanical knowledge has been shown to be spared (Hodges et al., 2000; Lesourd et al., 2016), while both functional and manipulation knowledge have been found to be impaired (Corbett, Jefferies, Burns, & Lambon Ralph, 2015; Negri, Lunardelli, Reverberi, Gigli, & Rumiati, 2007).

For instance, both AD and SD patients meet difficulties to recognize the good way to hold a tool in hand among several possibilities (i.e., manipulation knowledge) and fail to match pictures of objects that share the same function (i.e., functional knowledge). However, only AD patients are impaired to solve mechanical problems supposed to assess more specifically mechanical knowledge (a target is stuck in a box and has to be extracted using a particular tool). Thus, the global performance in pantomime of tool use may be explained by an impairment of manipulation, mechanical and functional knowledge in AD and by an impairment of manipulation and functional knowledge in SD.

More specifically, we shall examine the error profiles in AD and SD. In AD, both production and conception errors should be relatively frequent (Derouesné, Lagha-Pierucci, Thibault, Baudouin-Madec, & Lacomblez, 2000). In SD, given the semantic impairment, only conception errors should be over-represented. Then, we shall try to find the best predictors of conception and production errors in AD and SD patients. We hypothesize that conception errors will be explained by an impairment of functional knowledge, whereas production errors will be explained by an impairment of manipulation knowledge (Buxbaum, 2001; Rothi et al., 1991).

---

[1] "Manipulation knowledge" and "motor program" refer to the same concept, that is, a stored representation of the action associated with a particular tool (see also gesture engrams; Buxbaum, 2001). We chose to keep the term "motor program" because it is used as is by some authors (Bartolo & Cubelli, 2014; Niessen, Fink, & Weiss, 2014). For now, those terms will be used interchangeably.

# METHODS

## Participants

The study was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki. Local health authority ethics committees (CPP Ouest II Angers and ANSM) approved this study and informed consent was obtained for all participants. We recruited 30 patients with AD and 13 patients with SD from neurology units in Angers, Lyon, Rennes, and Grenoble in France. All cases were diagnosed by an experienced neurologist with respect to the standard, international consensus criteria. All AD patients met the NINDS-ADRDA criteria for probable AD (McKhann et al., 1984). All SD patients fulfilled previously proposed criteria for SD: anomia, impairment in single-word comprehension, and impoverished semantic knowledge with relative preservation of visuo-spatial abilities and day-to-day memory (Hodges, Graham, & Patterson, 1995).

Participants with a history of stroke or other neurological conditions were excluded from the study. As it is typical for these etiologies, AD patients were older than SD patients (age in years: AD = 76.6; SD = 67.4; $p < .01$; see Table 1). Moreover, SD patients received more years of education (AD = 9.1; SD = 12.5; $p < .05$). Thus, level of education and chronological age were both included in between group comparisons as covariates. The 30 control participants were recruited in Lyon and Angers and were matched in age with AD patients.

## Neuropsychological Assessment

In addition to follow-up consultations, neuropsychological data were collected in all of the participants with three standard tests: (1) The Mini Mental State Examination (Folstein, Folstein, & McHugh, 1975). (2) A French neuropsychological battery (the BEC 96 questionnaire, Signoret et al., 1989), composed of eight subtests administered in the following order: mental manipulation, orientation questions, general verbal reasoning, verbal fluency, visual recognition, verbal learning, naming of 12 black and white depicted objects, and visuo-constructive skills. Maximum score per subtest is 12 (total score = 96) with any score below 9 indicating pathological performance according to French normative data. The maximum total score is 96. (3) A fast frontal assessment battery (FAB; Dubois, Slachevsky, Litvan, & Pillon, 2000) that includes word-categorization, letter fluency, assessment of grasping, deferred imitation of movement sequence, and two conflict go-no-go tasks. Each of these six subtests is scored on a 3-point scale (total score = 18). Any score below 15 demonstrates executive dysfunction according to French normative data.

## Experimental Tasks

The experimental tasks were administered in the following order.

**Table 1**. Demographical data and neuropsychological assessment

| Test | Control<br>($n$ = 30) | AD<br>($n$ = 30) | SD<br>($n$ = 13) | AD *versus* SD<br>$p$-Level |
|---|---|---|---|---|
| Gender (women/men) | 20/10 | 20/10 | 6/7 | ns |
| Handedness (left/right) | 1/29 | 0/30 | 0/13 | ns |
| Age (years) | 75.2 (6.0) | 76.6 (7.1) | **67.4 (8.2)** | ** |
| Education (years) | 12.4 (4.8) | **9.1 (4.4)** | 12.5 (2.9)[b] | * |
| FAB (/18) | — | 12.8 (2.3)[c] | 13.3 (2.3)[c] | ns |
| MMSE (/30) | 27.3 (1.7) | **20.2 (2.8)** | **23.3 (4.6)**[b] | * |
| BEC 96 (/96)[a] | 87.8 (5.3) | **67.6 (9.3)** | **63.7 (14.8)**[b] | ns |
| Verbal learning | 10.7 (1.5) | **6.8 (2.7)** | **6.4 (2.8)**[b] | ns |
| Visual recognition | 10.8 (0.9) | **5.4 (2.2)** | **8.8 (2.7)**[b] | *** |
| Orientation | 11.5 (1.0) | **5.8 (3.9)** | 10.0 (2.7)[b] | ** |
| Visuo-constructive skills | 10.9 (1.5) | 9.8 (2.8) | 10.8 (2.2)[b] | ns |
| General reasoning | 9.1 (1.9) | 8.2 (2.1) | **6.4 (2.8)**[b] | * |
| Verbal fluency | 11.6 (1.1) | **9.8 (2.6)** | **5.4 (2.9)**[b] | *** |
| Naming | 11.5 (0.7) | **10.4 (1.8)** | **4.8 (2.9)**[b] | *** |
| Mental manipulation | 11.7 (1.6) | 11.5 (2.2) | 11.3 (2.6)[b] | ns |

*Note*. Between-groups comparisons were performed with Mann-Whitney $U$-tests, except for Gender and Handedness (Chi-2 analysis). Values in bold reveal pathological scores for patients relative to control. Values in brackets are standard deviations. AD = Alzheimer's disease; SD = semantic dementia; FAB = Frontal Assessment Battery at bedside; MMSE = Mini-Mental State Examination; BEC = Batterie d'Evaluation Cognitive.

[a] Every item of the BEC 96 was rated on a 12-points scale.

[b] Data not available for $n = 1$ participant.

[c] Data not available for $n = 2$ participants.

*$p < .05$.

**$p < .01$.

*** $p < .001$.

### Pantomime of tool use (PTU)

Ten familiar tools (plus 1 corrected, practice item) were presented one at a time on a vertical panel. Participants were asked to demonstrate the typical use of the tools without holding them in hand (i.e., pantomime on visual presentation of the tool). The examiner did not name the tools. The time limit was set to 20 s per item. Performance was videotaped and rated on a 3-point scale (maximum = 20): (2) the expected gesture was clearly recognizable and performed without hesitation; (1) the gesture was recognizable but contained errors or hesitations (i.e., spatiotemporal errors), or a part of the body was used as the tool (i.e., body-part as object error); (0) unrecognizable (i.e., content errors) or absence of any gesture (i.e., perplexity). Two independent raters coded videos from 10 control participants, 10 patients with Alzheimer's disease, and 5 patients with semantic dementia (approximately half of the whole data). Cohen's kappa coefficient indicated a very good inter-rater agreement ($K = .91$).

### Mechanical problem-solving task (MPS)

This test assessed the ability to solve mechanical problems with novel tools (Lesourd et al., 2016). It consisted in three different transparent boxes. A little red wooden cube or a little red wooden bead (i.e., the targets) was stuck inside each box. Participants were asked to extract the target out from the box using a given rod. Each box called for different mechanical actions (i.e., pushing, pulling, levering) and could be solved in two stages but not by hand, lucky movements, or trial-and-errors strategies. The time limit was 3 min for each box. The performance was videotaped and the time of achievement for each item was recorded. Performance was rated on a 4-point scale (maximum score = 9): (3) the target was extracted from the box within the time limit; (2) the participant went beyond the first stage of the problem; (1) the participant reached the target with the rod but did not fulfill the first stage; (0) the participant did not reach the target with the rod.

### Functional Matching task (FM)

This test made of 10 items (plus 1 corrected, practice item) assessed functional knowledge. Four images with different objects were presented below the picture of a tool (i.e., target stimulus). Participants were asked to select one out of the four pictures that best matched the target stimulus. The matching criterion was the function of the tool (e.g., jug/bottle). The foils showed tools that shared perceptual (e.g., jug/bowling pin), categorical (i.e., jug/fork), or no features (e.g., jug/scythe) with the target stimulus. Each correct answer given within 20 s was worth 1 point (maximum = 10).

### Recognition of tool manipulation (RTM)

This task assessed manipulation knowledge by asking participants to choose among four photographs the one that corresponded to the best way to hold a tool to use it with an object (e.g., saw/piece of wood). 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 showed the tool inappropriately held, incorrectly oriented in the hand or dangerously held. There were 10 items (plus one practice item), and 1 point was given for a correct answer given within 20 s (maximum = 10).

## Scoring System

### Quantitative assessment

In tool use tasks, ceiling effects are often observed in controls' performance (e.g., Lesourd et al., 2013a). To avoid this effect, we used an original methodology (see Lesourd et al., 2016), and we applied it to the four tasks of the present study. The principle was very similar to the one used in the Wechsler Adult Intelligence Scale (see for example, Wechsler, 1997).

The aim of our methodology was to create a composite score that takes into account the *time* spent by the participants to achieve the task. For each item of a given task, we computed 4 centiles on the whole distribution of achievement times of the control participants (i.e., $C_5$, $C_{25}$, $C_{75}$, and $C_{95}$). Then a score was attributed for each interval delimited by the centiles. The faster the time of completion, the greater the composite score. For all of the four tasks, if the time to carry out the accurate action was less than $C_5$, 10 points were accorded, if the completion time was comprised between $C_5$ and $C_{25}$, 8 points were accorded, if the completion time was comprised between $C_{25}$ and $C_{75}$, 6 points were accorded and if the completion time was comprised between $C_{75}$ and $C_{95}$, 4 points were accorded.

If the completion time was above $C_{95}$, the score remains unchanged. For instance, in the PTU task, if a participant produces accurately a pantomime with a completion time above $C_{95}$, only 2 points are accorded, in accordance with the scoring system of the PTU task. Finally, the new scores obtained for each condition for a participant were summed and gave a global composite score of completion for the task. After transformation of the data, the composite scores for the four tasks were normally distributed. The global composite scores of patients were computed relative to the centiles obtained from the distribution of control participants, so that the distributions of scores obtained in patient's groups and in the control group can be compared together. All the details of the data transformation are supplied in Supplementary Material.

### Error analysis

First, the gestures produced by both participants and patients during the PTU task were categorized as follows: correct or incorrect gestures. Then, incorrect gestures were subdivided into conception or production errors: *(i) Conception errors are of two kinds:* (1) content errors, in which actions are performed skillfully but out of context; (2) perplexity, in which no action is carried out with unmistakable sign of not knowing what to do. *(ii) Production errors are also of two kinds:* (1) spatiotemporal errors, the action performed is appropriate but poorly executed in the spatial dimension (e.g., incorrect plane of execution or mishandling of the tool if it were in hand) or in the temporal dimension (e.g., poor timing of execution); (2) body-part as object errors, the participant uses a part of his body to simulate the presence of the tool.

The proportion of each kind of gesture (i.e., content errors, perplexity, spatiotemporal errors, body-part as object errors, and correct gestures) was computed relatively to the total number of gestures produced for each group (i.e., control participants, AD and SD patients).

## Statistical Analysis

Each patient and each participant obtained (1) a composite score for each experimental task (i.e., PTU, FM, MPS, and RTM) as it has been described in method section and (2) a distribution of errors made during the PTU task.

Analyses of covariance (ANCOVAs) with level of education and chronological age as covariates and groups (three levels: Control participants, AD patients, and SD patients) as between-subject factor were conducted separately for each experimental task (i.e., PTU, MPS, FM, and RTM).

Multiple regressions analyses were used, within each participant group, to predict participants' abilities to pantomime tool use (i.e., PTU) and conception and production errors (i.e., raw scores), with MPS, FM, and RTM composite scores as predictors. The model with the highest adjusted $R^2$ was selected as the one that best accounted for participants' performance.

Chi-square tests were used to compare the distribution of errors in pantomime of tool use between participant groups. Standard residuals were computed for correct gestures, conception, and production errors. Errors with standard residuals greater than ±2 (Agresti, 2007) mean that these gestures are more represented or less represented than would be expected by chance.

All analyses were performed using R statistical software (R Development Core Team, 2008).

# RESULTS

## Neuropsychological Assessment

AD and SD patients exhibited different patterns of impairment across the sub-tests of BEC 96 (see Table 1). SD patients were severely impaired in tasks requiring verbal skills and semantic memory (i.e., verbal learning, verbal fluency, and naming) and showed relatively spared performance on tasks assessing non-verbal memory (i.e., orientation and visual recognition), whereas AD patients exhibited impairment in all tasks assessing memory (i.e., orientation, verbal learning, and visual recognition). These data are consistent with the diagnosis.

## Group Comparisons for Composite Scores

Results of group comparisons are displayed in Figure 1 (see also Supplementary Material for detailed means and standard deviations of composite scores). The results of the ANCOVAs revealed a significant effect of the variable Group on PTU composite scores, $F(2,68) = 22.57$, $MSE = 223.3$, $p < .001$, control participants ($M = 51.1$) performed better than AD ($M = 27.5$; $p < .001$) and SD patients ($M = 26$; $p < .001$), but there was no difference between AD and SD patients ($p = .95$). Furthermore, the ANCOVAs revealed significant effect of Group on MPS, $F(2,68) = 19.78$, $MSE = 17.4$, $p < .001$; on FM, $F(2,68) = 19.23$, $MSE = 307.3$, $p < .001$; and on RTM composite scores, $F(2,68) = 23.79$, $MSE = 352.8$, $p < .001$.

## Predictors of Global Performance of Pantomime of Tool Use and of Conception and Production Errors

Correlation matrix between predictors is displayed in Table 2. Multiple backward regressions were carried out for each group to assess the involvement of each experimental task in PTU scores and in conception and production errors (i.e., raw scores) (Table 3).

For control participants, with PTU as a dependent variable, a trend toward significance was found for MPS ($\beta = .35$; $p = .056$) as a predictor and the model accounted for 9% of the variance, $F(1,28) = 3.97$, $p = .056$, $R^2 = .09$. When production errors were predicted, RTM ($\beta = -.37$; $p < .05$) was a significant predictor and the model accounted for 11% of the variance, $F(1,28) = 4.56$, $p = .042$, $R^2 = .11$.

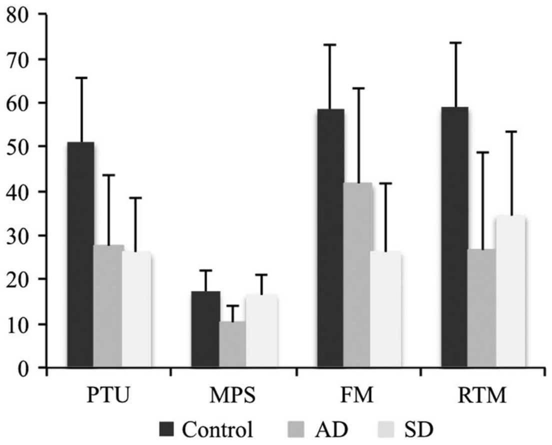

**Fig. 1.** Mean composite scores for pantomime of tool use, mechanical problem solving, functional matching, and recognition of tool manipulation as a function of group variable. PTU, pantomime of tool use; MPS, mechanical problem solving; FM, functional matching; RTM: recognition of tool manipulation. Bars are standard deviations.

**Table 2**. Correlation matrix between predictors (Pearson's product moment) in control group and AD and SD patients

| Control ($n$ = 30) | | | | AD ($n$ = 30) | | | | SD ($n$ = 13) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tasks | MPS | FM | RTM | Tasks | MPS | FM | RTM | Tasks | MPS | FM | RTM |
| MPS | | .11 | .38* | MPS | | .67** | .57** | MPS | | .23 | .06 |
| FM | | | .32 | FM | | | .57** | FM | | | .43 |
| RTM | | | | RTM | | | | RTM | | | |

*Note.* MPS = mechanical problem-solving; FM = functional matching; RTM = recognition of tool manipulation; AD = Alzheimer's disease; SD = semantic dementia
* $p < .05$.
** $p < .001$.

As control participants did not make any conception errors, no regression was conducted with this variable.

For AD patients, when PTU was predicted, MPS ($\beta$ = .41; $p < .05$) and RTM ($\beta$ = .43; $p < .05$) were significant predictors and the model accounted for 52% of the variance, $F(2,27) = 16.45$; $p < .001$; $R^2 = .52$. When production errors were predicted, no significant predictors were found. When conception errors were predicted, a trend toward significance was found for FM ($\beta = -.36$; $p = .053$) as predictor and the model accounted for 10% of the variance, $F(1,28) = 4.09$, $p = .053$, $R^2 = .10$. We did not find any correlation between production and conception errors in AD patients, $r = -.03$, $p$ = 89.

For SD patients, when PTU was predicted, no significant predictor was found. When production errors were predicted, FM ($\beta$ = .80; $p < .01$) was a significant predictor. MPS ($\beta = -.38$; $p = .07$) was also selected and the model accounted for 58% of the variance, $F(2,10) = 9.41$, $p < .01$, $R^2 = .58$. When conception errors were predicted, FM ($\beta = -.70$; $p < .01$) was a significant predictor. MPS ($\beta = .42$; $p = .08$) was also selected and the model accounted for 45% of the variance, $F(2,10) = 5.88$, $p < .05$, $R^2 = .45$. Moreover, we found a significant correlation between production and conception errors in SD patients, $r = -.62$, $p = .02$.

**Table 3**. Multiple regressions with pantomime of tool use, conception errors, and production errors as dependent variables, and MPS, FM, and RTM as predictors for control participants and AD and SD patients

| | | $\beta$ | $t$ | $p$ | $R^2_{adj}$ |
|---|---|---|---|---|---|
| *Predictors of pantomime of tool use* | | | | | |
| Control | MPS | .35 | 2.0 | ◆ | .09 |
| AD | MPS | .41 | 2.6 | * | .52 |
| | RTM | .43 | 2.7 | * | |
| SD | — | — | — | — | — |
| *Predictors of conception errors* | | | | | |
| Control | — | — | — | — | — |
| AD | FM | −.36 | −2.0 | ◆ | .10 |
| SD | FM | −.70 | −3.2 | ** | .45 |
| | MPS | .42 | 1.9 | ◆ | |
| *Predictors of production errors* | | | | | |
| Control | RTM | −.37 | −2.1 | * | .11 |
| AD | — | — | — | — | — |
| SD | FM | .80 | 4.2 | ** | .58 |
| | MPS | −.38 | −2.0 | ◆ | |

*Note.* MPS = mechanical problem solving; RTM = recognition of tool manipulation; FM = functional matching; AD = Alzheimer's disease; SD = semantic dementia.
◆$p < .08$.
*$p < .05$.
** $p < .01$.

## Comparison of Error Profiles between Groups

Chi-square tests revealed that the proportion of errors and correct gestures differed significantly among AD, SD patients and control participants, $\chi^2 = 83.19$, df = 4, $p < .01$. As it can be seen in Figure 2, correct gestures were significantly less represented in both AD (50%; $p < .001$) and SD (53.1%; $p = .02$) patients than would be expected by chance. Both conception (12%; $p < .01$) and production (38%; $p < .001$) errors were significantly more represented in AD patients than would be expected by chance while only conception (22.3%; $p < .001$) errors were more represented in SD patients than would be expected by chance. Of interest, concerning production errors, the proportion of "body-part as object" errors seemed to be comparable across the three groups (i.e., Control, 3.3%; AD, 5.7%; SD, 4.6%) whereas it was not the case for spatiotemporal errors (i.e., Control, 21.7%; AD, 32.3%; SD, 20.0%; Table 4).

## DISCUSSION

The aim of the present study was twofold. First, as mechanical, manipulation, and functional knowledge are supposed to be required to pantomime the use of tools, we investigated the role of each of these cognitive components in participants' ability to perform pantomime of tool use. Second, we explored the nature of errors (i.e., production and conception) made by AD and SD patients, and we identified the cognitive components that may explain these errors. Concerning the prediction of pantomime of tool use performance, our hypotheses are partially validated. In AD patients, recognition of tool manipulation and mechanical problem-solving

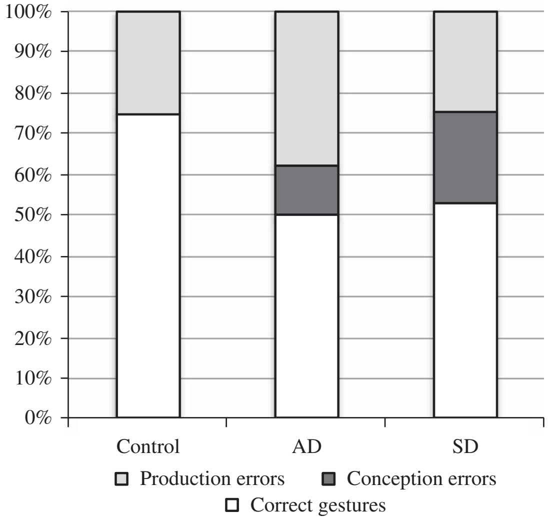

**Fig. 2.** Proportion of correct and incorrect gestures (i.e., conception and production errors) made by control participants and Alzheimer's disease (AD) and semantic dementia (SD) patients.

scores were selected as predictors whereas recognition of tool manipulation, mechanical knowledge, and functional knowledge are impaired in AD.

Concerning SD patients, no predictors were selected, whereas functional and manipulation knowledge are impaired in SD. In line with our hypotheses, production and conception errors were significantly more represented than would be expected by chance in AD, whereas only conception errors were significantly more represented than would be expected by chance in SD. Of interest, no predictors were selected in AD to explain production errors whereas manipulation knowledge impairment is known to be involved in those kinds of errors. In line with our predictions, functional matching scores were good predictors of conception errors in SD, validating the involvement of functional knowledge in conception errors.

Furthermore, we found an important amount of production errors in control participants, questioning the meaning and the underlying cognitive components of this kind of error. We will discuss, in turn, the link between mechanical and manipulation knowledge, the nature of errors made during the PTU task and notably the meaning of production errors. Finally, we will address the multi-determined feature of the PTU task.

**Table 4**. Contingency table of the nature of gestures produced during pantomime of tool use task for the three groups

| | | Production errors | | Conception errors | |
|---|---|---|---|---|---|
| | Correct gestures | Spatiotemporal | Body-part object | Content | Perplexity |
| Control | 75.0% | 21.7% | 3.3% | 0% | 0% |
| AD | 50.0% | 32.3% | 5.7% | 6.7% | 5.3% |
| SD | 53.1% | 20.0% | 4.6% | 11.5% | 10.8% |

## Manipulation Knowledge *versus* Mechanical Knowledge

When global performance of pantomime of tool use was predicted, we found that mechanical problem solving was a good predictor in AD patients and control participants, whereas recognition of tool manipulation was a significant predictor only in AD patients. In the long-standing tradition of study of apraxia, a prerequisite for pantomiming object use is the activation of the motor schema (i.e., manipulation knowledge; Niessen, Fink, & Weiss, 2014), so manipulation knowledge should be activated since we need to pantomime the use of a tool.

However, this is not the case in this study because mechanical problem solving was found to be a more robust predictor of pantomime of tool use. Obviously, we cannot exclude that mechanical problem solving and pantomime of tool use are both production tasks while recognition of tool manipulation is an observational task. It could explain why mechanical problem-solving task was found to be a good predictor of the PTU use task while recognition of tool manipulation was not. Thus, to rule out this hypothesis, further studies have to develop mechanical knowledge tasks that do not require gesture production. We will now examine several hypotheses that can be raised to explain the link between manipulation knowledge and mechanical knowledge.

The inferior parietal lobe has been suggested to support either mechanical knowledge (Goldenberg & Hagmann, 1998; Goldenberg & Spatt, 2009; Jarry et al., 2013; Osiurak & Badets, 2016; Osiurak et al., 2009) or manipulation knowledge (Buxbaum, Kyle, Grossman, & Coslett, 2007; Buxbaum, Kyle, & Menon, 2005; Heilman, Rothi, & Valenstein, 1982). So, given that both manipulation knowledge and mechanical knowledge might share the same neural substrate, a first possibility is that manipulation and mechanical knowledge can coexist and be involved in different processes.

In line with this prediction, Vingerhoets and coworkers (2011) found a striking similarity in brain activation when participants were asked to pantomime the use of familiar and unfamiliar tools. In the manipulation-based approach, familiar tool use would be supported by manipulation knowledge while unfamiliar tool use would be supported by mechanical knowledge. However, in our study, pantomime of familiar tools was better explained by mechanical problem solving, which is not predicted by the manipulation-based approach.

A second possibility is that mechanical and manipulation knowledge coexist and are complementary processes. For instance, mechanical knowledge would be in charge of forming a mental simulation of the mechanical action to be made (i.e., interaction between a tool and an object) then constraining the activation of appropriate manipulation knowledge (i.e., interaction between the tool and the hand). In line with this hypothesis, we found that, in AD patients, both mechanical problem solving and recognition of tool manipulation were significant predictors of pantomime of tool use. Moreover, we found significant correlations between mechanical problem solving and recognition of tool manipulation tasks in control participants and in AD patients, suggesting a common process supporting manipulation and mechanical knowledge.

Finally, a third possibility is that mechanical and manipulation knowledge are complementary processes but are not supported by the same neural substrate. A recent finding from a neuroimaging meta-analysis (Reynaud, Lesourd, Navarro, & Osiurak, 2016) showed that processing of tool–object interaction (i.e., mechanical knowledge) was specifically associated with inferior parietal lobe activation (PF area), whereas processing of tool–hand interaction (i.e., manipulation knowledge) was associated with several cortical activations including intra-parietal sulcus and posterior inferior temporal cortex. This result is in line with a recent lesion map study that showed that manipulation knowledge impairment is associated with posterior temporal lesions (Kalénine, Buxbaum & Coslett, 2010). In sum, further research is needed to disentangle between these different possibilities.

## Nature of Errors Made during Pantomime of Tool Use

When looking at profile errors, we found that control participants produced more correct gestures (75.0%) than AD (50.0%) and SD (53.1%) patients. This observation corroborates previous evidence that pantomime of tool use is impaired in AD (for a review, see Lesourd et al., 2013a, 2013b) and confirms that it is also the case in SD. More particularly, we found that AD patients committed a significant number of conception and production errors while only conception errors were over-represented in SD patients.

Furthermore, functional matching was found to be a robust predictor of conception errors for both AD and SD patients. Indeed we found that functional matching composite scores were linked by a negative regression coefficient to the amount of conception errors in SD and to a lesser extent in AD. Thus an increasing of conception errors is explained by a decreasing in functional matching composite scores. In other words, impairment of functional knowledge is involved in conception errors in AD (Adlam, Bozeat, Arnold, Watson, & Hodges, 2006) and SD patients (Hodges et al., 2000).

Concerning production errors, we observed different results among the three groups: recognition of tool manipulation was a good predictor of production errors in control participants, functional matching and mechanical problem solving were good predictors in SD patients, and there was no significant predictor in AD patients. This result is quite surprising; given that recognition of tool manipulation is supposed to assess manipulation knowledge, production errors should be a hallmark of impaired manipulation knowledge (Rothi et al., 1991).

Thus several hypotheses could be proposed to explain this result. First, one may assume that recognition of tool manipulation task does not assess manipulation knowledge; so, it would not be surprising that production errors are not consistently explained by recognition of tool manipulation. However, this task is basically linked to the study of manipulation knowledge (Buxbaum & Saffran, 2002; Buxbaum, 2001; Buxbaum, Sirigu, Schwartz, & Klatzky, 2003; Rothi et al., 1991). Second, manipulation knowledge is not mandatory to produce pantomime of tool use, so production errors could be explained by many other cognitive components impairment (e.g., working memory; Bartolo, Cubelli, Della Sala, & Drei, 2003) but we will discuss this point later.

We also need to discuss an interesting dissociation between functional matching and mechanical problem-solving regression coefficient signs that explain the amount of conception and production errors in SD. More particularly, we found positive regression coefficients for mechanical problem solving and functional matching associated with conception and production errors, respectively. Thus, it suggests that an increase of the amount of errors is explained by a knowledge improvement, which is questionable. Concerning the negative functional matching regression coefficient, we found a negative correlation between production and conception errors in SD, suggesting that these two kinds of errors are not independent in this disease. Indeed, according to our scoring system, an error cannot be of two kinds. Thus, when the amount of production errors increases the amount of conception error may decrease. As we showed that conception errors increase when functional matching composite scores decrease, it explains why production errors and functional matching are positively linked in SD.

More particularly, the greater the conceptual impairment of SD patients, the more they committed conception errors and, as a result, the less they made production errors. Concerning the positive mechanical problem-solving regression coefficient, we had no *a priori* hypotheses about its involvement in error production and more particularly in conception errors. Some authors argued that only mechanical and functional knowledge are needed when we use tools (Goldenberg & Hagmann, 1998; Goldenberg, 2013); so, these two kinds of knowledge should also be able to explain the errors made when we use tools. In this approach, in case of functional impairment, using tools should rely only on mechanical knowledge, notably the ability to infer the function of the tool from its structure[2] (Goldenberg & Hagmann, 1998; Vaina & Jaulent, 1991).

However, a good ability to infer the function of the tool from its structure does not lead necessarily to a good conventional use of the tool (i.e., the usage; Osiurak, Jarry, & Le Gall, 2010), because it may exist a hidden link between the tool and the object typically associated (Hartmann, Goldenberg, Daumüller, & Hermsdörfer, 2005). Then, it could explain why ability to infer function from structure is

---

[2] Here, we use the concept of inference of function from structure (Goldenberg & Hagmann, 1998) and mechanical knowledge (Lesourd et al., 2015; see also Osiurak et al., 2009 for technical reasoning) interchangeably, although there are subtle differences between these concepts. However, these differences are beyond the scope of the present study.

positively associated with conception errors (i.e., the usage of the tool). This latter hypothesis has to be taken with caution and further studies have to explored the involvement of mechanical knowledge in conception and production errors.

However, we have to acknowledge that the presence of both positive beta coefficients (i.e., mechanical problem solving and functional matching) may lie on our scoring system characteristics. Indeed, the commission of a conception error rules out the possibility of committing a production error on the same item; on the other hand the commission of a production error on a given item limits the probability of a conception error to occur on the same item. For instance, a body-part as object error may prevent the production of a conception error, while other kinds of production errors may obscure subtle conception errors. The non-independence of production and conception errors type could be the reason for both observed positive Beta coefficients. Thus, it may represent a limitation of the scoring system adopted here.

## Are Pantomimes Communicative Gestures?

We would like to discuss a surprising result from our study. Indeed, control participants made 25% of production errors (i.e., 21.7% of spatiotemporal and 3.3% of body-part as object errors), but it seems exaggerated to conclude about the presence of apraxia in normal aging. One may assume that our definition of production errors could have led to a significant number of production errors in control participants. In the literature on apraxia, there are as many studies as different scoring systems, notably in the PTU task, that lead to an important variability among the results reported (e.g., in AD patients, see Lesourd et al., 2013). However, in our study, we used consistent definition of production errors (e.g., McDonald, Tate, & Rigby, 1994) and the inter-rater agreement in our PTU task was high. Thus other scoring systems would have probably found similar results from ours.

So, why have we observed such a proportion of production errors in control participants? An answer may come from the meaning of the spatiotemporal error itself. For instance, for screwing an electric bulb, participants often produced the correct rotational movement without, nevertheless, opening the hand. Although kinematic recording of the hand aperture differs from pantomime to real tool use (Laimgruber, Goldenberg, & Hermsdörfer, 2005), here, a complete feature of the action was missing (i.e., the aperture of the hand), and the pantomime was scored as a production error, and not as a conception error, as the pantomime was still recognizable.

However, this kind of error does not traduce necessarily an impairment of any kind of knowledge. For instance, "body-part as object" errors, which are also considered as production errors, consist in simplifying a gesture by using a part of the body to mimic the tool (e.g., the use of the index finger as a toothbrush) and are commonly made by healthy subjects and chosen as a correct response in recognition of tool manipulation tasks (McDonald et al., 1994). So, production errors (i.e., spatiotemporal and body-part as object errors) do not alter *per se* the processing of the gesture (i.e., its meaning) by an external observer.

In healthy controls, they may either reflect attempts to improve the recognition of the gesture by others (e.g., the hand aperture is not a discriminant feature of gestures so it is not considered to avoid adding some "noise"). Thus, pantomime of tool use can also be viewed as communicative gestures (Goldenberg, 2013) and production errors in control participants may reflect an attempt to simplify a complex gesture to better communicate the meaning of this gesture to the examiner. In this view, participants may tend to focus on features of gestures that evoke the content of the action, but they may have low demands with regard to the production itself, which could explain the high rate of production errors in our PTU task. Further studies are needed to investigate the link between communicative skills and the ability to produce pantomimes of tool use.

## Pantomime of Tool Use: A Multi-determined Task

In this study, we explored the cognitive bases of pantomime of tool use by investigating the roles of functional knowledge, manipulation knowledge and mechanical knowledge. To our knowledge, it is the first demonstration of the involvement of mechanical knowledge in pantomime of tool use. Actually, it is quite logical; considering that this task is rarely experimented in everyday life, it can be viewed as a non-routine problem-solving task (i.e., the reconstruction hypothesis; Osiurak et al., 2011; see also Osiurak et al., 2010). For a long time, pantomime of tool use has been considered as a meaningful, transitive movement which requires the activation of motor schema or routines (e.g., Niessen et al., 2014).

However, the following definition of pantomime of tool use seems to be more in line with our findings: "The pantomimes […] are recognizable but rarely experienced; they are unusual […] but meaningful gestures; at the same time they are intransitive gestures because no object is actually used but they reproduce the way objects are held and used. Given that pantomimes are not available in long-term memory, they have to be constructed *de novo*" (Bartolo & Cubelli, 2014, p. 297; see also Osiurak et al., 2011 for a similar view).

For all that, only 10% of the performance in pantomime of tool use was explained by mechanical knowledge in control participants. This suggests that other components are involved in pantomiming the use of tools and confirms the complexity of this task (Bartolo & Cubelli, 2014). For instance, previous works have pointed out that pantomimes can rely on working memory (Bartolo et al., 2003). Indeed, to pantomime the use of a tool on visual presentation, it is necessary to imagine the tool in hand (e.g., a hammer), the object (e.g., a nail), and the action (e.g., hammering), and then to maintain this representation until the action has been performed. Once the representation of the tool, the object, and the action has been created, it is still necessary to maintain it to convert the shape, movement, and position of the hand into a pantomime. Further works may investigate the roles of working memory and other cognitive components using the methodology we followed in this study.

## A Final Word

To conclude, pantomime of tool use will probably keep its secret a little longer, but our study showed that pantomime of tool use on visual presentation has more to do with problem solving than with the automatic activation of tool-related motor schemata. Finally, mechanical knowledge is added on the long list of the cognitive components that are supposed to be involved in pantomime (i.e., functional knowledge, manipulation knowledge, communicative skills, working memory, etc.). In all likelihood, the pantomime of tool use is a powerful screening task, but its interest might be relatively limited when time comes to infer impaired cognitive mechanisms.

## ACKNOWLEDGMENTS

This work was supported by grants from ANR (AgenceNationale pour la Recherche; Project Démences et Utilisationd'Outils/ Dementia and Tool Use, N°ANR 2011 MALZ 006 03; D. Le Gall, F. Osiurak), and was performed within the framework of the LABEX CORTEX (ANR-11-LABX-0042) of Université de Lyon, within the program "Investissementsd'Avenir" (ANR-11- IDEX--0007; F. Osiurak,) operated by the French National Research Agency (ANR). The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Supplementary material

Supplementary material(s) can be found online. Please visit journals.cambridge.org/jid_INS

## REFERENCES

Adlam, A.R., Bozeat, S., Arnold, R., Watson, P., & Hodges, J.R. (2006). Semantic knowledge in mild cognitive impairment and mild Alzheimer's disease. *Cortex*, *42*(5), 675–684. http://doi.org/10.1016/S0010-9452(08)70404-0

Agresti, A. (2007). *An introduction to categorical analysis*. Hoboken: Wiley.

Bartolo, A., & Cubelli, R. (2014). The cognitive models of limb apraxia and the specific properties of meaningful gestures. *Cortex*, *57*, 297–298. http://doi.org/10.1016/j.cortex.2014.01.007

Bartolo, A., Cubelli, R., Della Sala, S., & Drei, S. (2003). Pantomimes are special gestures which rely on working memory. *Brain and Cognition*, *53*(3), 483–494. http://doi.org/10.1016/S0278-2626(03)00209-4

Buxbaum, L.J. (2001). Ideomotor apraxia: A call to action. *Neurocase*, *7*, 445–448.

Buxbaum, L.J., Kyle, K., Grossman, M., & Coslett, H.B. (2007). Left inferior parietal representations for skilled hand-object interactions: Evidence from stroke and corticobasal degeneration. *Cortex*, *43*(3), 411–423. http://doi.org/10.1016/S0010-9452(08)70466-0

Buxbaum, L.J., Kyle, K.M., & Menon, R. (2005). On beyond mirror neurons: Internal representations subserving imitation and recognition of skilled object-related actions in humans. *Cognitive Brain Research*, *25*(1), 226–239. http://doi.org/10.1016/j.cogbrainres.2005.05.014

Buxbaum, L.J., & Saffran, E.M. (2002). Knowledge of object manipulation and object function: Dissociations in apraxic and nonapraxic subjects. *Brain and Language*, *82*(2), 179–199. http://doi.org/10.1016/S0093-934X(02)00014-7

Buxbaum, L.J., Sirigu, A., Schwartz, M.F., & Klatzky, R. (2003). Cognitive representations of hand posture in ideomotor apraxia. *Neuropsychologia*, *41*(8), 1091–1113. http://doi.org/10.1016/S0028-3932(02)00314-7

Corbett, F., Jefferies, E., Burns, A., & Lambon Ralph, M.A. (2015). Deregulated semantic cognition contributes to object-use deficits in Alzheimer's disease: A comparison with semantic aphasia and semantic dementia. *Journal of Neuropsychology*, *9*, 219–241. http://doi.org/10.1111/jnp.12047

Derouesné, C., Lagha-Pierucci, S., Thibault, S., Baudouin-Madec, V., & Lacomblez, L. (2000). Apraxic disturbances in patients with mild to moderate Alzheimer's disease. *Neuropsychologia*, *38*(13), 1760–1769. http://doi.org/10.1016/S0028-3932(00)00081-6

Dubois, B., Slachevsky, A., Litvan, I., & Pillon, B. (2000). The FAB: A frontal assessment battery at bedside. *Neurology*, *55*(11), 1621–1626. http://doi.org/10.1212/WNL.57.3.565

Folstein, M.F., Folstein, S.E., & McHugh, P.R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198. http://doi.org/10.1016/0022-3956(75)90026-6

Goldenberg, G. (2013). *Apraxia: The cognitive side of motor control*. Oxford: Oxford University Press, http://doi.org/10.1093/acprof:oso/9780199591510.001.0001

Goldenberg, G., & Hagmann, S. (1998). Tool use and mechanical problem solving in apraxia. *Neuropsychologia*, *36*(7), 581–589. http://doi.org/S0028-3932(97)00165-6 [pii]

Goldenberg, G., Hartmann, K., & Schlott, I. (2003). Defective pantomime of object use in left brain damage: Apraxia or asymbolia? *Neuropsychologia*, *41*(12), 1565–1573. http://doi.org/10.1016/S0028-3932(03)00120-9

Goldenberg, G., & Spatt, J. (2009). The neural basis of tool use. *Brain*, *132*(6), 1645–1655. http://doi.org/10.1093/brain/awp080

Hartmann, K., Goldenberg, G., Daumüller, M., & Hermsdörfer, J. (2005). It takes the whole brain to make a cup of coffee: The neuropsychology of naturalistic actions involving technical devices. *Neuropsychologia*, *43*(4), 625–637. http://doi.org/10.1016/j.neuropsychologia.2004.07.015

Heilman, K.M., Rothi, L.J., & Valenstein, E. (1982). Two forms of ideomotor apraxia. *Neurology*, *32*, 342–346.

Hodges, J.R., Bozeat, S., Lambon Ralph, M.A., Patterson, K., & Spatt, J. (2000). The role of conceptual knowledge in object use: Evidence from semantic dementia. *Brain*, *123*, 1913–1925.

Hodges, J.R., Graham, N., & Patterson, K. (1995). Charting the progression in semantic dementia: Implications for the organisation of semantic memory. *Memory*, *3*(3-4), 463–495. http://doi.org/10.1080/09658219508253161

Jarry, C., Osiurak, F., Delafuys, D., Chauviré, V., Etcharry-Bouyx, F., & Le Gall, D. (2013). Apraxia of tool use: More evidence for the technical reasoning hypothesis. *Cortex*, *49*(9), 2322–2333. http://doi.org/10.1016/j.cortex.2013.02.011

Kalénine, S., Buxbaum, L.J., & Coslett, H.B. (2010). Critical brain regions for action recognition: Lesion symptom mapping in left hemisphere stroke. *Brain*, *133*(11), 3269–3280. http://doi.org/10.1093/brain/awq210

Laimgruber, K., Goldenberg, G., & Hermsdörfer, J. (2005). Manual and hemispheric asymmetries in the execution of actual and pantomimed prehension. *Neuropsychologia*, *43*, 682–692.

Lesourd, M., Baumard, J., Jarry, C., Etcharry-Bouyx, F., Belliard, S., Moreaud, O., … Osiurak, F. (2016). Mechanical problem-solving strategies in Alzheimer's disease and semantic dementia. *Neuropsychology*, *30*(6), 612–623. http://doi.org/10.1037/neu0000241

Lesourd, M., Le Gall, D., Baumard, J., Croisile, B., Jarry, C., & Osiurak, F. (2013a). Apraxia and Alzheimer's disease: Review and perspectives. *Neuropsychology Review*, *23*(3), 234–256. http://doi.org/10.1007/s11065-013-9235-4

Lesourd, M., Le Gall, D., Baumard, J., Croisile, B., Jarry, C., & Osiurak, F. (2013b). Apraxie et maladie d'Alzheimer. *Revue de Neuropsychologie*, *5*(3), 213–222. http://doi.org/10.1684/nrp.2013.0273

McDonald, S., Tate, R.L., & Rigby, J. (1994). Error types in ideomotor apraxia: A qualitative analysis. *Brain and Cognition*, *25*(2), 250–270. http://doi.org/10.1006/brcg.1994.1035

McKhann, G., Drachman, D., Folstein, M., Katzman, R., Price, D., & Stadlan, E.M. (1984). Clinical diagnosis of Alzheimer's disease: Report of the NINCDS-ADRDA Work Group under the auspices of Department of Health and Human Services Task Force on Alzheimer's Disease. *Neurology*, *34*, 939–944. http://doi.org/10.1212/WNL.34.7.939

Negri, G.A., Lunardelli, A., Reverberi, C., Gigli, G.L., & Rumiati, R.I. (2007). Degraded semantic knowledge and accurate object use. *Cortex*, *43*(3), 376–388. http://doi.org/10.1016/S0010-9452(08)70463-5

Niessen, E., Fink, G.R., & Weiss, P.H. (2014). Apraxia, pantomime and the parietal cortex. *Neuroimage: Clinical*, *5*, 42–52. http://doi.org/10.1016/j.nicl.2014.05.017

Ochipa, C., Rothi, L.J.G., & Heilman, K.M. (1989). Ideational apraxia: A deficit in tool selection and use. *Annals of Neurology*, *25*(2), 190–193. http://doi.org/10.1002/ana.410250214

Osiurak, F., & Badets, A. (2016). Tool use and affordance: Manipulation-based versus reasoning-based approaches. *Psychological Review*, [Epub ahead of print]. http://doi.org/10.1037/rev0000027

Osiurak, F., Jarry, C., Allain, P., Aubin, G., Etcharry-Bouyx, F., Richard, I., … Le Gall, D. (2009). Unusual use of objects after unilateral brain damage. The technical reasoning model. *Cortex*, *45*(6), 769–783. http://doi.org/10.1016/j.cortex.2008.06.013

Osiurak, F., Jarry, C., & Le Gall, D. (2010). Grasping the affordances, understanding the reasoning: Toward a dialectical theory of human tool use. *Psychological Review*, *117*(2), 517–540. http://doi.org/10.1037/a0019004

Osiurak, F., Jarry, C., & Le Gall, D. (2011). Re-examining the gesture engram hypothesis. New perspectives on apraxia of tool use. *Neuropsychologia*, *49*(3), 299–312. http://doi.org/10.1016/j.neuropsychologia.2010.12.041

Poeck, K. (1983). Ideational apraxia. *Journal of Neurology*, *230*(1), 1–5. http://doi.org/10.1007/BF00313591

R Development Core Team. (2008). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.r-project.org

Reynaud, E., Lesourd, M., Navarro, J., & Osiurak, F. (2016). On the neurocognitive origins of human tool use a critical review of neuroimaging data. *Neuroscience & Biobehavioral Reviews*, *64*, 421–437. http://doi.org/10.1016/j.neubiorev.2016.03.009

Rothi, L.J.G., Ochipa, C., & Heilman, K.M. (1991). A cognitive neuropsychological model of limb praxis. *Cognitive Neuropsychology*, *8*(6), 443–458. http://doi.org/10.1080/02643299108253382

Signoret, J.L., Allard, M., Benoit, N., Bolgert, F., Bonvarlet, M., & Eustache, F. (1989). *Batterie d'Evaluation Cognitive - BEC 96*. Paris: Fondation IPSEN.

Vaina, L.M., & Jaulent, M.C. (1991). Object structure and action requirements: A compatibility model for functional recognition. *International Journal of Intelligent Systems*, *6*, 313–336.

Vingerhoets, G., Vandekerckhove, E., Honoré, P., Vandemaele, P., & Achten, E. (2011). Neural correlates of pantomiming familiar and unfamiliar tools: Action semantics versus mechanical problem solving? *Human Brain Mapping*, *32*(6), 905–918. http://doi.org/10.1002/hbm.21078

Wechsler, D. (1997). *Wechsler Adult Intelligence Scale - 3rd Edition (WAIS-3)*. San Antonio: TX: Harcourt Assessment.