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1 **PHYSICAL UNDERSTANDING IN NEURODEGENERATIVE**
2 **DISEASES**

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30 **ABSTRACT**

31 This quantitative review of $n = 13$ studies gives an overview of physical understanding
32 (i.e., the ability to represent and use the laws of physics to interact with the physical world)
33 impairments in Alzheimer's disease (AD), semantic dementia (SD), and corticobasal
34 syndrome (CBS). In the context of dementia, it has been studied mainly with mechanical
35 problem-solving tests. Performance in these tests depends mainly on the left inferior temporal
36 lobe. Physical understanding, along with semantic tool knowledge supported by the temporal
37 lobes, underlie familiar tool use. Whether physical understanding deficits accurately predict
38 tool use impairments in this population remains an open issue. This review shows that: (1) SD
39 patients have apraxia of tool use because of semantic tool knowledge deficits, but normal
40 performance in tests of physical understanding; (2) AD and CBS patients show impaired
41 performance in mechanical problem-solving tests; (3) This is probably not caused by intrinsic
42 deficits of physical understanding, but rather by additional cognitive impairments (in AD) or
43 motor deficits (in CBS); (4) As a result, the performance in mechanical problem-solving tests
44 is not a good predictor of familiar tool use in dementia; (5) Actual deficits of physical
45 understanding are probably observed only in late stages of neurodegenerative diseases, and
46 associated with functional loss. Future directions are suggested, with particular emphasis on
47 task differences and inclusion criteria.

48 *Keywords: technical reasoning, mechanical knowledge; causal reasoning; analogical*
49 *reasoning; apraxia; tool use.*

50 **1. INTRODUCTION**

51 Humans, like other animals, are biological entities immersed in a physical world. A
52 fundamental issue at the edge of physics and psychology is, therefore, to understand how the
53 laws of physics shape the human mind, and conversely, how individuals represent and use the
54 physical laws (hereafter referred to as “physical understanding”). In an ecological context,
55 physical understanding has been proposed to be at the root of humans’ highly flexible tool use
56 skills, tool making, and analogical reasoning (e.g., anticipating that lifting a heavy object will
57 call for more muscular strength than lifting a light object; understanding that a glass is heavy
58 and solid enough to smash a spider, but not to hammer a nail; anticipating how to grasp a tool
59 as a function of its subsequent use; Allen et al., 2020; Goldenberg & Spatt, 2009; Goldenberg,
60 2009; Osiurak, 2014; Osiurak et al., 2008, 2009, 2010, 2011; Osiurak & Reynaud, 2020;
61 Povinelli, 2000; Vaesen, 2012). There has been evidence for a double dissociation between
62 physical understanding (“how things work”; e.g. judging in which direction an unstable tower
63 of blocks will fall) and psychological understanding (“how people work”; Kamps et al., 2017;
64 Osiurak & Reynaud, 2020), suggesting that physical understanding is a specific mental ability.
65 While the latter has long been studied by asking healthy adults to make predictions regarding
66 physical events that are going to happen in a near future (e.g., Caramazza et al., 1981;
67 McCloskey, 1980, 1983a, 1983b), improving our comprehension of how neurological diseases
68 in general, and neurodegenerative diseases in particular, alter physical understanding may
69 lead to significant breakthrough in this field (Hubbard, 2019). Studying the ecology of
70 physical understanding may in turn help to better understand the loss of autonomy of some
71 patients, and contribute to the differential diagnosis. The literature is, however, sparse on this
72 topic, while there have been more studies on tool use skills. Focusing on the latter may
73 provide insight on physical understanding, for three reasons: (1) in an ecological setting, tool

74 use is probably the most frequent activity that would call for physical understanding (e.g., we
75 use tools more frequently than we solve abstract physics problems); (2) some links have been
76 demonstrated between tool use and physical understanding in patients with stroke; (3) to our
77 knowledge, there is literature on how patients with dementia solve concrete tool use situations
78 but not abstract physics problems.

79 It turns out that patients with dementia typically demonstrate loss of autonomy, a
80 diagnostic criterion of all neurodegenerative diseases (Crutch et al., 2013, 2017; Gorno-
81 Tempini et al., 2011; McKhann et al., 2011). As a matter of fact, apraxia of tool use (i.e., the
82 inability to properly use familiar or novel tools and objects, that cannot be explained by motor
83 or sensory deficit, or by attentional or language impairments; Dovern et al., 2012; Jarry et al.,
84 2013; Osiurak et al., 2008, 2009, 2010, 2011, 2013; Rothi et al., 1991, 1997; Wheaton &
85 Hallett, 2007; see also Giovannetti et al., 2002, 2006) has been consistently documented in
86 these patients (Baumard et al., 2016; Bozeat et al., 2002; Buchmann et al., 2020; Hodges,
87 2000; Jarry et al., 2020; Leiguarda et al., 2002; Lesourd et al., 2013, 2016). The use of
88 familiar tools is a complex task that may rely on multiple cognitive processes, like semantic
89 tool knowledge (Roy & Square, 1985; Stamenova et al., 2010, 2012), working memory
90 (Bartolo et al., 2003; Cubelli et al., 2000), executive functioning (Goldenberg et al., 2007;
91 Hartmann et al., 2005; see also Martyr & Clare, 2012), or body representations (Buxbaum,
92 2001; Goldenberg, 1995). A critical issue is, therefore, to understand which processes are at
93 stake in the apraxia of tool use presented by patients with neurodegenerative diseases, as well
94 as the role of physical understanding in this syndrome. A growing body of anthropological
95 and neuropsychological literature has linked physical understanding to the ability to reason on
96 the mechanical properties offered by tools and objects (Baillargeon, 1994; Baumard et al.,
97 2016; Beck et al., 2011; Bozeat et al., 2002; Goldenberg & Spatt, 2009; Goldenberg, 2009;
98 Goldenberg & Hagmann, 1998; Hodges, 2000; Lesourd et al., 2016; Ochipa et al., 1992;

99 Osiurak, 2014; Osiurak et al., 2010, 2011, 2013). Physical understanding has been assessed in
100 a variety of tasks (to be described below) hereafter referred to as mechanical problem-solving
101 (MPS) tests. The latter are tool use tasks in which participants are asked to use novel tools and
102 objects, meaning that the performance cannot rely on prior tool knowledge (e.g., making a
103 hook with metal wire to extract a target out of a box; (Baumard et al., 2016; Beck et al., 2011;
104 Heilman et al., 1997; Jarry et al., 2013; Lesourd et al., 2016; Ochipa et al., 1992; Osiurak et
105 al., 2013). In view of positive correlations between performance in MPS tasks and in familiar
106 tool use tasks in patients with left-hemisphere damage, physical understanding appears
107 necessary to perform even conventional actions and activities of daily living (Buchmann &
108 Randerath, 2017; Goldenberg & Hagmann, 1998; Heilman et al., 1997; Jarry et al., 2013;
109 Lesourd et al., 2019; Osiurak et al., 2013; Osiurak & Reynaud, 2020; Reynaud et al., 2016).

110 Since patients with neurodegenerative diseases may have apraxia of tool use, the
111 question arises whether they also demonstrate impaired physical understanding, a topic that
112 has received renewed interest in recent years. The goal of this review was, therefore, twofold.
113 The first goal was to provide a full picture of the performance of patients with
114 neurodegenerative diseases in tasks engaging physical understanding. To anticipate our
115 findings, this has been mainly studied with mechanical problem-solving tests, thus the review
116 will rapidly focus on these tests. The second goal was to study the links between familiar tool
117 use and mechanical problem-solving skills, on the one hand because both have been strongly
118 linked in the literature, and on the other hand because in an ecological context, tool use is
119 probably the most frequent situation in which humans have to reason on physical principles
120 (e.g., solving intuitive physics paradigms without actually acting on the physical world is
121 actually rare in everyday life). Importantly, dementia is far from being a monolithic category,
122 thus different patients diagnosed with different neurodegenerative syndromes may have
123 apraxia of tool use either because of physical understanding deficits *per se* or because of other

124 cognitive impairments (e.g., semantic deficits). This in turn implies to discuss the mental
125 processes that underlie human tool use. The findings will therefore be discussed in the light of
126 the Four Constraints Theory of tool use or 4CT (Osiurak, 2014), the only integrative theory
127 that acknowledges a critical role of physical understanding in tool use. To address these
128 different issues, sections 2.1 and 2.2 review the concepts and assessment methods of physical
129 understanding; section 2.3 describes the core assumptions of the Four Constraint theory as
130 well as the neural bases of tool use and physical understanding; then section 3 details and
131 discusses the literature on physical understanding impairments in dementia, and their potential
132 links to tool use.

133 **2. THE CONCEPT OF PHYSICAL UNDERSTANDING**

134 **2.1. The many names of physical understanding**

135 **2.1.1. Intuitive physics**

136 The human kind has developed a very complex technological culture over time (Osiurak
137 & Reynaud, 2020; Reynaud et al., 2016), to the point that the products of this culture have
138 become a threat to the ecosystem itself. One may think that humans are, therefore, particularly
139 efficient in their understanding of the physical laws. This is, however, not always the case, as
140 demonstrated by studies on false beliefs that humans have about the laws that govern the
141 physical world (e.g., causality, planetary movements; see also “implicit theories”, Plaks,
142 2017). This fact has been captured by researchers with different terms like “intuitive physics”,
143 defined as *“the knowledge underlying the human ability to understand the physical*
144 *environment and interact with objects and substances that undergo dynamic state changes,*
145 *making at least approximate predictions about how observed events will unfold”* (Kubricht,
146 2017, p. 750). This concept has replaced the one of “naïve physics” that was used in early

147 research studies (Caramazza et al., 1981; McCloskey, 1980, 1983b). The term “folk physics”
148 has also been used in some studies, and refers to the spontaneous understanding one has of the
149 physical world (Povinelli, 2000; Silva & Silva, 2006). An important aspect of intuitive
150 physics is that the predictions that individuals make are not always consistent with the
151 principles of Newtonian physics – hence the term “intuitive”. The field of intuitive physics
152 has investigated people’s misconceptions when they try to apply physical laws to concrete
153 situations. There has been a number of paradigms in the literature: Predicting the trajectory of
154 a falling object dropped from a plane; predicting the trajectory of a ball when it comes out of
155 a C-shaped tube; predicting the trajectory of a pendulum bob after the string is cut; drawing
156 the water level in a tilted glass (for a review, see Kubricht, 2017). In these paradigms, a non-
157 negligible percentage of adult participants (sometimes the majority of them) tends to make
158 predictions that violate the laws of physics. As an example, in the C-shaped, or curved tube
159 paradigm, half of the participants erroneously indicated that the ball would continue along a
160 curved trajectory (McCloskey et al., 1980). Doing so, they demonstrated a “naïve impetus”
161 theory, that is the belief, inherited from medieval theorists, that an object submitted to forces
162 acquires an internal force itself (i.e., the impetus) in the direction of its motion (McCloskey &
163 Kargon, 1988). In fact, Newtonian physics rather predict a straight line trajectory in the
164 absence of external force. Similarly, the Galileo bias (Oberle et al., 2005) corresponds to
165 naïve beliefs as to the effects of air resistance on objects. To sum up, individuals do not use
166 the laws of physics when they solve such problems, but rather an approximation of these laws
167 based on mental constructs. The latter are judgment heuristics that are implicit and not always
168 accurate regarding the laws of physics, but that require less effort than explicitly
169 understanding these laws, while being accurate enough in everyday life situations requiring
170 fast responses (Hubbard, 2019; Kozhevnikov & Hegarty, 2001).

171 **2.1.2. Mechanical reasoning**

172 Other concepts have been used to refer to physical understanding. “Mechanical
173 reasoning” is the mental process that allows individuals to make inferences, namely, to derive
174 information about how things move – mechanics being the branch of physics that studies
175 motion (Hegarty, 2004). It has been used to describe how individuals solve spatial problems
176 (e.g., gear rotation problems), and associated with mental simulation and spatial cognition
177 (Mitko & Fischer, 2020). In all likelihood, some classical pencil-and-paper trajectory
178 prediction paradigms (see section 2.1.1) can be solved thanks to mechanical reasoning.

179 That being said, this concept has only limited scope and does not explain how
180 individuals may reason on non-spatial physical properties of tools and objects (e.g., material,
181 texture, weight, density, opacity). Imagine, for example, that you want to set up fence posts in
182 your garden. Spatial cognition and mental simulation may allow you to visualize the final
183 result, and to predict the outcome of each intermediate step (e.g., the orientation and relative
184 position of each post relative to the soil and to each other; Allen et al., 2020; Osiurak, 2014).
185 But you will also need to anticipate that your garden is made of loamy soil that will not drain
186 the rain very well, and hence to buy posts made of rot-resistant wood, unless you protect it
187 with a piece of rust-resistant metal. To fix the posts vertically, you also need to understand
188 that cement is a better solution than sand or rocks. Spatial cognition alone could not allow
189 humans to reason on these interactions because they are based on physical, rather than spatial
190 properties. As a matter of fact, MPS impairments have been documented in patients with left
191 hemisphere stroke, while visual-spatial impairments typically follow right hemisphere lesions
192 (e.g., Goldenberg & Hagmann, 1998; for a review, see Baumard et al., 2014). To sum up,
193 motion prediction and hence some classical intuitive physics tasks can probably be solved
194 thanks to mechanical reasoning, but the latter is different from the tool-related reasoning
195 further described below.

196 **2.1.3. Physical understanding in the neuropsychological literature**

197 In the neuropsychological literature, physical understanding has been studied in patients
198 with apraxia of tool use. In fact, the “apraxia of tool use” wording has been preferred to more
199 classical categories like “ideational apraxia” or “conceptual apraxia” (i.e., the inability to use
200 familiar tools due to semantic loss; De Renzi & Lucchelli, 1988; Ochipa et al., 1992; Rothi et
201 al., 1991; Roy & Square, 1985), to refer to deficits in the use of both familiar and novel tools,
202 and to suggest that the core deficit lies in the inability to reason about the physical properties
203 of tools and objects (Osiurak, Aubin, Allain, Jarry, Etcharry-Bouyx, et al., 2008; Osiurak et
204 al., 2009, 2010, 2011, 2013; Osiurak, 2014). Neurological, especially stroke patients may
205 indeed demonstrate impaired tool use (Baumard et al., 2014; Buchmann et al., 2020;
206 Buchmann & Randerath, 2017; Goldenberg, 2009; Goldenberg & Hagmann, 1998;
207 Goldenberg & Spatt, 2009; Jarry et al., 2013; Osiurak et al., 2009, 2013). In some studies,
208 mechanical problem-solving skills have fallen into the broad scope of “non-verbal
209 impairments” (Bozeat et al., 2000, 2002; Hodges et al., 1999, 2000), while others have seen
210 physical understanding as the expression of specific modes of reasoning. “Mechanical
211 knowledge” has been defined as a specific subtype of knowledge of the mechanical function
212 of tools and objects, allowing to understand the mechanical nature of problems; to understand
213 the advantages that tools may afford, and hence to select tools; to develop new strategies
214 while solving mechanical puzzles; and to make tools (Heilman et al., 1997; Ochipa et al.,
215 1992; see also “practical knowledge”, Roy & Square, 1985). More recently, it has been
216 defined as non-declarative knowledge about the physical principles underlying tool use,
217 acquired through experience (Osiurak & Reynaud, 2020). “Structural inference” has been
218 defined as the ability to infer the proper function of novel tools based on the visual analysis of
219 their structure, independently of prior knowledge (Goldenberg & Hagmann, 1998). The same
220 authors (Goldenberg & Spatt, 2009; Goldenberg, 2009) have later made a link between motor
221 functions and reasoning by assuming that during tool use actions, the “categorical

222 apprehension” of mechanical relationships between tools and objects, or between different
223 parts of multi-part objects, is a necessary condition to generate an optimal “chain” linking the
224 body (e.g., the arm and hand posture) to the output of the action (e.g., the recipient of tool
225 use). For example, it is the alignment of the screwdriver and the screw that constraints how to
226 hold the screwdriver, and not the contrary. “Technical reasoning” is close to this proposal, and
227 has been defined as the ability to determine possible mechanical relationships between tools
228 and objects, as a function of properties of each (Osiurak, 2014; Osiurak et al., 2010, 2011).
229 The common point between structural inference, categorical apprehension, and technical
230 reasoning, is to consider that mechanical problem-solving tasks call for dynamic, bottom-up
231 reasoning, rather than retrieval of knowledge from memory. The technical reasoning
232 hypothesis, in particular, assumes that tools have no intrinsic, decontextualized properties, and
233 that the possible mechanical actions one can perform with tools are inferred from context-
234 dependent relations between a tool and an object (i.e., one and the same tool may allow many
235 different tool-object interactions). For the sake of clarity, and seeing the similarities between
236 the abovementioned cognitive processes, we will hereafter refer to “physical understanding”
237 only to refer to the ability to reason on the mechanical properties of tools and objects.

238 **2.1.4. Physical understanding is implicit and pragmatic**

239 Before going further, it is necessary to fully understand the nature of physical
240 understanding. Why are humans sometimes bad at solving simple physics problems? This can
241 be explained by the fact that physical understanding is partly based on prior knowledge that
242 individuals have about the physical world (“technical expertise”; Osiurak & Reynaud, 2020).
243 Developmental and comparative studies embracing the innate/acquired debate have suggested
244 that human infants have a core ability to understand basic interactions between objects, or
245 physics intuitions (e.g., objects move as connected wholes; they do not interact at a distance),
246 that are later enriched through domain-specific experience of the physical world (see the "core

247 knowledge theory" of Spelke & Kinzler, 2007; see also Baillargeon, 1994; Baillargeon et al.,
248 1990, 1992; Needham & Baillargeon, 1993; Remigereau et al., 2016). This likely reflects the
249 existence of an internal model acquired through both ontogenesis (e.g., the continuous
250 experience of gravity and its consequences rapidly allows infants to make predictions on the
251 behavior of moving objects) and phylogenesis (e.g., all living species on Earth are exposed to
252 gravity, hence the development and selection of mental representations fitting to it). This
253 amounts to considering that physical understanding is pragmatic in nature: It intervenes and
254 develops as individuals face new physical events and principles.

255 Physical understanding is not only pragmatic, but it is also implicit. As emphasized by
256 Osiurak and Reynaud (2020), it may be difficult for individuals to make explicit what they
257 actually understand about physical principles (e.g., one may perform a cutting action, and
258 hence understand the principles behind it, without being able to make explicit that this action
259 results from the interaction of a sharp and hard tool with a softer object; see Osiurak, 2014;
260 Gatewood, 1985; Wynn & Coolidge, 2014). After all, infant studies have shown that babies
261 can understand physical interactions even before the maturation of language (Baillargeon,
262 1998). So, implicit understanding of physical principles, but not explicit, conventional
263 knowledge, may allow fruitful interactions with the physical world (see also Hubbard,
264 2019b).

265 If physical understanding is implicit, pragmatic, and supposedly efficient, then why are
266 healthy adults bad at solving physics problems? Actually, this is the case only under certain
267 circumstances. Indeed, the way problems are presented influences the performance, and
268 correlational studies have reported only moderate associations between the performance
269 obtained by healthy adults in different intuitive physics paradigms (Riener et al., 2005). The
270 context-dependent nature of physical understanding, along with subject-dependent
271 experience, may explain why individuals may have what appears like false or "magical"

272 beliefs when trying to predict physical events, and why the performance of healthy adults is
273 not consistent across seemingly identical intuitive physics paradigms. For instance,
274 participants make erroneous predictions in the classical curved tube problem (i.e., predicting
275 the trajectory of an object upon exiting from the tube), whereas they improve when asked to
276 discriminate normal or abnormal trajectories based on dynamic animations (Kaiser et al.,
277 1992) – a situation that is closer to naturalistic interactions with the physical world. Replacing
278 the ball with water in this paradigm (hence likening the tube to a hose) improves the
279 performance (Kaiser et al., 1986). Oberle et al. (2005) have found that the Galileo bias (i.e.,
280 the tendency to erroneously ignore air resistance during problem solving) is actually stronger
281 in physics students, probably because they are generally asked to ignore air resistance when
282 they solve physics problems.

283 To sum up, the performance in tests of physical understanding improves (i.e.,
284 predictions are closer to the laws of physics) in familiar and concrete situations; when
285 performance can rely on contextual information; and when stimuli are dynamic and not static
286 (for a review, see Kubricht et al., 2017). This raises the issue of the complex mapping of
287 sensory information and causality judgment (Sanborn, 2013). In an ecological context, where
288 individuals' judgments can rely on perception, contextual cues and prior experience, and are
289 “teleologically-driven” (i.e., the need to make a decision on subsequent actions, which is not
290 needed in abstract, classical intuitive physics tasks; Smith et al., 2018), causality judgments
291 are actually close to Newtonian mechanics. It means that explicit judgment errors may not
292 reflect inefficient physical understanding but rather sensory uncertainty and probabilistic
293 computations (see also Battaglia et al., 2013). The distinction between mechanical (spatial)
294 reasoning and technical reasoning may also explain why healthy individuals may fail to solve
295 some motion prediction tasks but use tools in a very efficient manner (see section 2.1.3). It

296 means, also, that concrete tests involving actual tools and materials are probably better tests of
297 physical understanding than abstract thought experiments.

298 **2.2. How to assess physical understanding**

299 In the next section we will focus on tests that have been used in the field of dementia.
300 To our knowledge, there have been no intuitive physics studies in this field (e.g., a Pubmed
301 search on March 2021 returns no results with these keywords), other than studies based on
302 Piagetian paradigms (Piaget & Inhelder, 1963). In these paradigms, individuals are typically
303 asked to compare quantities (e.g., mass, liquid, area, number) presented in different formats
304 (e.g., if one pours the water contained in a high and tight glass into a low and large glass, has
305 the quantity of water changed?). To answer correctly, participants thus have to understand the
306 laws of conservation and reversibility, making these paradigms close to physical
307 understanding tasks. Adult-like performance in this task is obtained at 7-12 years of age, and
308 corresponds to the concrete operational stage of development in the Piagetian taxonomy
309 (Matteson et al., 1996).

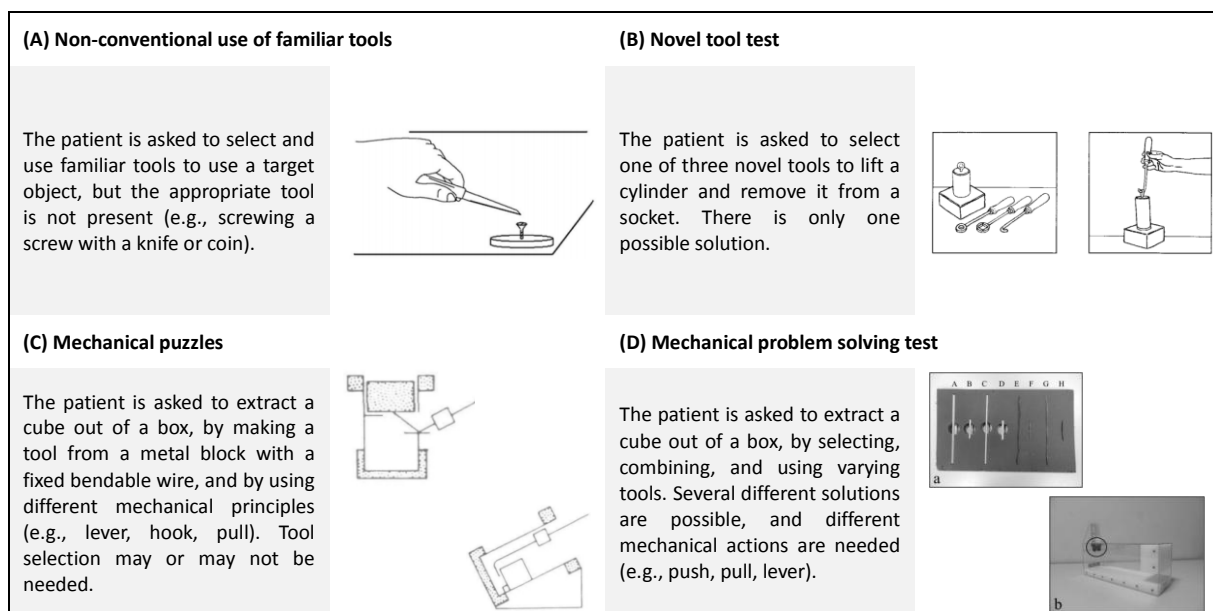
310 Physical understanding, that said, has been more extensively investigated in apraxia
311 studies. Four types of tests have been employed. In the unusual use of object and alternative
312 tool selection tests (Figure 1A), participants are asked to select and/or use familiar tools in an
313 unconventional manner (e.g., Derouesné et al., 2000; Osiurak et al., 2009). It means that tool
314 use cannot rely on explicit semantic tool knowledge, and instead has to rely on the analysis of
315 potential tool-object mechanical interactions. The limitation of these tests is that patients
316 presumably have to inhibit the canonical function of the tool to be able to innovate. This is a
317 problem with regard to functional fixedness (i.e., a cognitive bias that limits tool-related
318 creativity with familiar tools; Duncker, 1945), hence the creation of mechanical problem
319 solving tests inspired by animal studies (e.g., Povinelli, 2000). In these tests, individuals are

320 motivated to extract a target object out of a box by recourse to different novel tools and
321 mechanical actions (e.g., push, pull, lever, hook). There have been some variations of this test,
322 which common ground is that the solution has to be generated from scratch, rather than based
323 on semantic tool knowledge. As a result, these tests control for semantic tool knowledge, and
324 the performance relies purely on physical understanding. Contrary to classical problems used
325 to assess executive functions (e.g., the Tower of London test, Shallice, 1982), the number of
326 steps toward the solution is limited, meaning that these problems tend to control for working
327 memory and planning skills as well. As a matter of fact, mechanical problems and multi-step
328 problems are sensitive to parietal lobe lesions and dysexecutive syndrome, respectively
329 (Goldenberg et al., 2007; Hartmann et al., 2005). In the novel tool test (Buchmann &
330 Randerath, 2017; Goldenberg & Hagmann, 1998; Hodges et al., 1999; Figure 1B),
331 participants are asked to select and use one of three novel tools, with the goal of lifting a
332 wooden cylinder out of a socket. Nine cylinders are presented, and two distinct scores are
333 collected for tool selection (independently of tool use) and tool application (independently of
334 tool selection). Mechanical puzzles (Figure 1C) have rather put the emphasis on tool making
335 as well as on the variety of mechanical actions needed to complete the eight items (Ochipa et
336 al., 1992). In the eponym mechanical problem solving test (Figure 1D), participants are asked
337 to extract a target out of a box by selecting, combining, and using up to eight novel tools that
338 vary on length, diameter, material, bendability, and color. It is similar to the two latter tests,
339 with four main differences. First, problem solving cannot be based on mere spatial cognition,
340 contrary to both spatial problems used in mechanical reasoning studies (Hegarty, 2004), and
341 the novel tool test, in which comparing the shape of the tools and the shape of the cylinder
342 may be sufficient to solve the problem. In contrast, the tools presented in the MPS test are
343 visually very similar, thus forcing participants to reason on physical properties like
344 bendability or rigidity. Second, contrary to the mechanical puzzles, the target cannot be

345 reached using the fingers. Not only does it force participants to use tools, but it also makes the
346 test usable with aphasic patients who could misunderstand the instruction of using a tool.
347 Third, there are multiple solutions, meaning that participants have to make “the best choice”
348 among several possible mechanical principles. As a result, it presumably puts higher loads on
349 decision-making grounded in physical understanding. Fourth, it has been designed to assess
350 MPS under two conditions: with choice, or without choice. In the choice condition, the
351 participants are given all the eight tools to solve the problem, so that the number of potential
352 mechanical interactions is high. In the no-choice condition, the examiner gives the participant
353 only one, useful tool. This condition puts lower loads on visual exploration and tool selection,
354 but the patient still has to understand which tool-box interactions are either relevant or
355 irrelevant to the goal of extracting the cube.

356

357



358 **Figure 1. Examples of tests of physical understanding.** The common point between these tests is that success
359 requires to reason about the physical attributes of tools and objects. Pictures are from (A) Osiurak et al. (2009);
360 (B) Goldenberg & Hagmann (1998); (C) Ochipa et al. (1992); (D) Lesourd et al. (2016).

361

362 **2.3. The neurocognitive bases of tool use**

363 Physical understanding has been proposed to be a key process, but not the only process
364 behind human tool use. Actually, there has been a debate between a memory-based
365 hypothesis, according to which tool use depends on stored representations of gestures
366 themselves, and a reasoning-based hypothesis that gives a prominent place to physical
367 understanding (Buxbaum et al., 2015; Osiurak & Le Gall, 2015). Solving this debate is
368 beyond the goal of the present review. The next section focuses on the most integrated model
369 of tool use within the reasoning-based approach: The four constraints theory (Osiurak, 2014).

370 **2.3.1. The Four Constraints Theory of tool use**

371 The 4CT assumes that familiar tool use is a kind of problem-solving situation in that it
372 implies to overcome some constraints (e.g., using the best available tool, making hypotheses
373 as to more efficient tools). This relies on four dissociable mental processes: Physical
374 understanding, semantic reasoning, mental simulation, and working memory. All of these
375 processes operate at a conceptual level, upstream of motor production.

376 Since physical understanding is implicit and pragmatic, it cannot be reduced to a kind of
377 explicit, semantic knowledge. McCloskey et al. (1980, 1983a, 1983b) initially demonstrated
378 that students with formal physics instruction may still use heuristics to formulate (incorrect)
379 predictions regarding moving objects. The neuropsychological literature has provided strong
380 arguments for a dissociation between semantic tool knowledge (i.e., knowledge about the
381 conventional function and context of use of tools and objects) and physical understanding. For
382 instance, patients with left hemisphere stroke and apraxia of tool use may commit “severe”
383 errors (e.g., eating soup with a fork; trying to press toothpaste out of a closed tube) that cannot
384 be explained by missing tool knowledge (Goldenberg & Hagmann, 1998). There is now
385 substantial evidence for a dissociation between familiar or novel tool use on the one hand, and

386 semantic tool knowledge on the other hand (Bartolo et al., 2007; Baumard et al., 2016; Bozeat
387 et al., 2002; Buxbaum et al., 1997; Buxbaum & Saffran, 2002; Goldenberg & Spatt, 2009;
388 Hodges et al., 1999, 2000; Negri et al., 2007; Osiurak & Badets, 2016; Silveri & Ciccarelli,
389 2009). On this ground, the 4CT assumes that tool use depends not only on semantic tool
390 knowledge, but also on physical understanding. Both cognitive domains may nonetheless
391 interact during familiar tool use (Osiurak, 2014). Imagine, for example, that you want to cut a
392 piece of bread. Based on physical understanding alone, a knife, a saw, or even a chopper,
393 share similar properties that are all useful to perform a “cutting” action. Semantic tool
394 knowledge narrows the possibilities, and allows to select the kitchen knife, even though other
395 tools may offer similar technical properties. The ability to mentally navigate through and
396 within semantic categories to make canonical choices of tools is called “semantic reasoning”
397 in the 4CT.

398 Mental simulation also plays a role to implement the one solution selected in the course
399 of action, to simulate the mechanical action, and to predict the future state of objects (e.g.,
400 Hegarty, 2004; Kubricht et al., 2017; Osiurak, 2014). It may be helpful to preclude some tools
401 that would not be comfortable to use (e.g., chainsaw), or that are too far in space (e.g., one
402 may select the tools she/he has even if they are not fully appropriate to the task, instead of
403 going out to buy a better tool). Finally, a participation of working memory is needed to
404 maintain subgoals throughout task performance, especially in long or complex action
405 sequences.

406 Importantly, these four cognitive components are not parallel routes to action execution.
407 They are better viewed as cognitive layers that may be more or less necessary depending on
408 the task. For example, novel tool use calls for physical understanding but not for semantic
409 reasoning, while familiar tool use calls for both. It means that a physical understanding deficit
410 should always be associated with both familiar and novel tool use impairments. This

411 fractionation of the tool use system also allows predictions regarding different
412 neurodegenerative diseases. For example, patients showing isolated semantic deficits should
413 be able to use novel, but not familiar tools, while patients with physical understanding deficits
414 should have difficulties using both.

415 **2.3.2. The neural bases of physical understanding**

416 Some of the cognitive components included in the 4CT have been associated with
417 specific brain regions. Of particular interest is the dissociation between a ventral pathway
418 underlying semantic reasoning, and a dorsal pathway underlying physical understanding and
419 mental simulation. Imaging studies have consistently reported that physical understanding
420 relies on frontal-parietal networks encompassing dorsal premotor and supplementary areas,
421 the medial/lateral frontal cortex, anterior portions of the parietal lobe, intraparietal sulcus and
422 supramarginal gyrus (Fischer et al., 2016; Han et al., 2011; Mason & Just, 2016; but see also
423 Fugelsang et al., 2005, who rather found a right-lateralized network for causal reasoning).
424 Even though discrepancy in testing procedures prevents us from drawing firm conclusions on
425 the neural bases of intuitive physics paradigms (an issue that is beyond the scope of this
426 review), there is remarkable overlap between these regions and brain regions that underlie
427 tool use (Binkofski & Buxbaum, 2013; Buxbaum, 2017; Buxbaum & Kalénine, 2010; Orban
428 & Caruana, 2014) and mechanical problem solving skills (Goldenberg & Spatt, 2009;
429 Goldenberg, 2009; Reynaud et al., 2016, 2019).

430 A significant body of evidence has established the existence of a left-lateralized network
431 for tool use. Liepmann (1905, 1920; see also Goldenberg, 2003) first demonstrated that
432 apraxia was caused by lesions of the left hemisphere. Importantly, patients may exhibit severe
433 difficulties when using not only familiar, but also novel tools (Bartolo et al., 2007;
434 Goldenberg et al., 2007; Goldenberg & Hagmann, 1998; Hartmann et al., 2005; Heilman et

435 al., 1997; Jarry et al., 2013; Osiurak et al., 2009). Patients with left hemisphere stroke have
436 more difficulties in the unusual use of objects test (Osiurak et al., 2009), in the novel tool test
437 (Bartolo et al., 2007; Buchmann et al., 2020; Buchmann & Randerath, 2017; Goldenberg &
438 Spatt, 2009; Goldenberg, 2009; Goldenberg et al., 2007; Goldenberg & Hagmann, 1998;
439 Hartmann et al., 2005), in mechanical puzzles (Heilman et al., 1997), and in the mechanical
440 problem-solving test (Jarry et al., 2013; Lesourd et al., 2016; Osiurak et al., 2013; for a
441 review, see Baumard et al., 2014), in comparison with healthy controls and patients with right
442 hemisphere stroke. Recent meta-analyses have strongly suggested that the left area PF (a
443 subregion of the supramarginal gyrus) is critical to physical understanding, in both action
444 execution and action observation paradigms (Figure 2; Osiurak & Reynaud, 2020; Reynaud et
445 al., 2016, 2019; see also Osiurak et al., 2020). Impairment in tasks assessing semantic tool
446 knowledge, in contrast, has been associated with temporal lobe lesions (Binkofski &
447 Buxbaum, 2013; Buxbaum, 2001, 2017; Buxbaum & Kalénine, 2010; Goldenberg & Spatt,
448 2009), while mental simulation probably depends on superior parietal brain regions (see
449 Osiurak, 2014; Osiurak & Badets, 2016).

450 It turns out that the temporal and parietal lobes are lesion sites for three
451 neurodegenerative diseases: Alzheimer's disease, semantic dementia, and corticobasal
452 syndrome (Figure 2). Such lesions are progressive in nature, and typically more widespread
453 than in stroke patients, yet they are relatively circumscribed in the first stages of the disease,
454 and they evolve in a stereotyped and progressive manner (e.g., temporal lobe lesions in
455 semantic dementia, frontal-parietal and subcortical lesions in corticobasal degeneration, and
456 more widespread lesions in Alzheimer's disease; Felician et al., 2003). As a result, these
457 syndromes are relevant clinical models to study how specific brain lesions may alter physical
458 understanding in particular, and tool use in general.

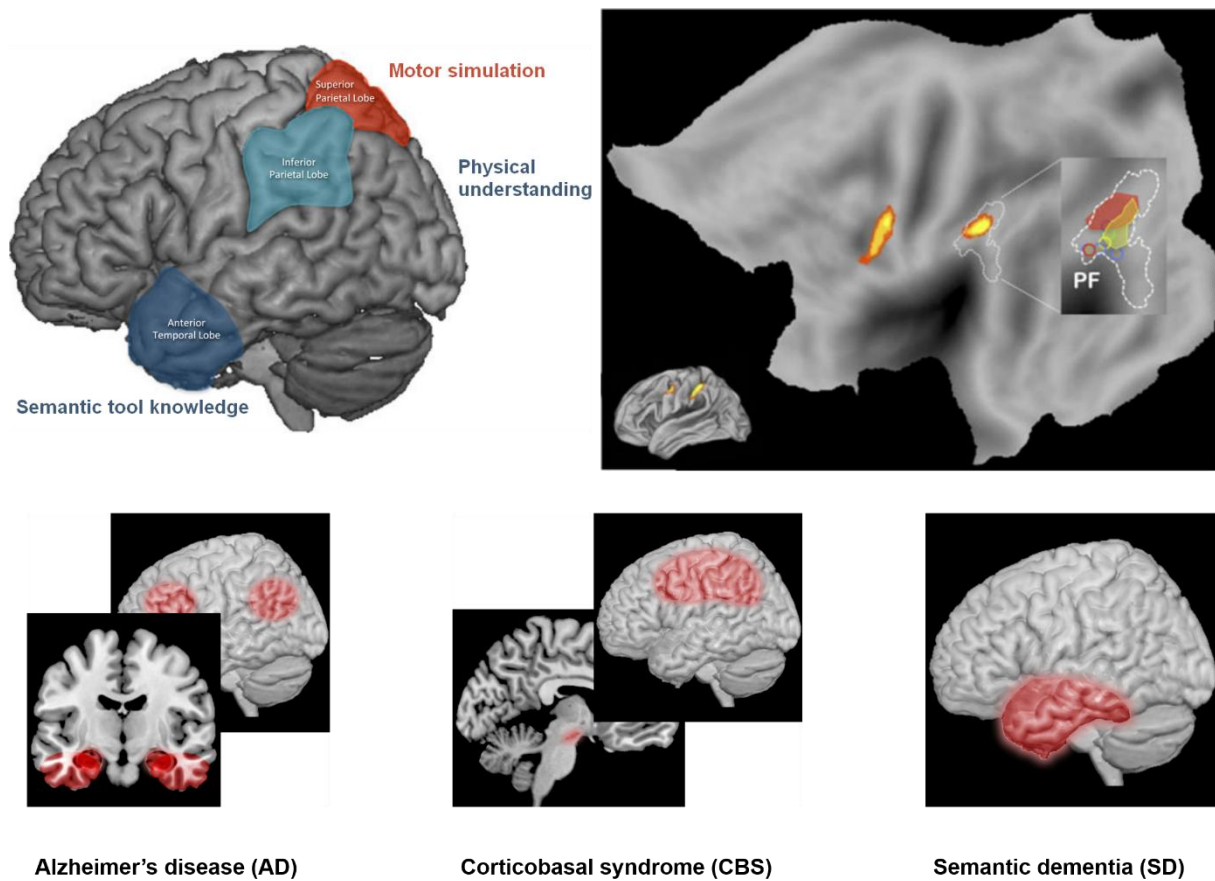


Figure 2. The neural bases of physical understanding and tool use. Upper panel, left: according to the 4CT of tool use, physical understanding and motor simulation are key components of familiar and novel tool use. Semantic tool knowledge is needed to use familiar tools in a conventional manner. Upper panel, right: Results from a neuroimaging meta-analysis study on tool use (Reynaud et al., 2016). Tasks requiring physical understanding were associated with activations of the area PF in the left hemisphere (in red in the zoomed picture). Lower panel: Schematic representation of typical lesion sites of Alzheimer's disease, corticobasal syndrome, and semantic dementia.

468 **3. PHYSICAL UNDERSTANDING IN**

469 **NEURODEGENERATIVE DISEASES**

470 Dementia is not a monolithic category, and different clinical presentations have been
471 described, corresponding to different patterns of cortical atrophy (Seeley et al., 2009). Given
472 that physical understanding depends on parietal brain regions, it could be predicted that
473 clinical syndromes involving degeneration of these regions (i.e., Alzheimer’s disease,
474 corticobasal syndrome) would be associated with physical understanding impairments, and
475 hence, tool use impairments. Similarly, degeneration of temporal brain regions (as in semantic
476 dementia) could result in the selective loss of semantic tool knowledge interfering with
477 familiar, but not novel tool use. This section will review the literature on physical
478 understanding and tool use skills in the field of neurodegenerative diseases.

479 **3.1. Methodological considerations**

480 **3.1.1. Research and selection of studies**

481 To prepare this review, we performed a Title/Abstract Pubmed search on Jan 2021,
482 using the following keywords: intuitive/folk/naïve physics, causal reasoning/thinking, magical
483 thinking, impetus, momentum, gravity/gravitation, Piagetian, mechanical
484 knowledge/reasoning/intelligence, technical reasoning, mechanical problem-solving, and
485 dementia, aging, Alzheimer’s disease. Pubmed returned 196 results, including many
486 duplicates. We also added some studies from our own reference management software.
487 Overall, 13 English-language studies were relevant to the topic of the review. Three of these
488 studies used Piagetian paradigms (Emery & Breslau, 1987; Matteson et al., 1996; Thornbury,
489 1992), while the remaining ten studies (Table 1) focused on mechanical problem-solving tests

490 (Figure 1) in Alzheimer's disease (AD), semantic dementia (SD), and corticobasal syndrome
491 (CBS).

492 **3.1.2. Data extraction**

493 We then extracted the scores of patients and healthy controls on these tests, as well as
494 data on familiar tool use where available, with the intention to study whether physical
495 understanding is, or is not, a good predictor of familiar tool use in neurodegenerative diseases.
496 The mean score of healthy controls and patients was available in most studies. Only figures
497 were available in five studies (Bozeat et al., 2002; Buchmann et al., 2020; Hodges, 2000;
498 Hodges et al., 1999; Ochipa et al., 1992). In these cases, the mean scores of healthy controls
499 and patients were imputed from visual inspection: We measured values on the y-axis (in
500 pixels) and applied the rule of three to estimate the score (e.g., for a y-axis with a 0-100 scale,
501 the maximum score corresponded to 472 pixels, and the patient's score corresponded to 400
502 pixels, so the estimated mean score was $400 * 100 / 472 = 84.7$).

503 **3.1.3. Methodological considerations**

504 We found substantial methodological discrepancy in the literature. The most obvious
505 one is the use of different mechanical problem-solving tests to assess very similar
506 psychological constructs (Figure 1). Furthermore, physical understanding may be assessed
507 with or without choice of tools (e.g., Lesourd et al., 2016; Ochipa et al., 1992). Tool selection
508 and tool manipulation have been coded separately in some studies (Bozeat et al., 2002;
509 Hodges et al., 2000; Spatt et al., 2002) while in other studies, scores captured both selection
510 and manipulation (Baumard et al., 2016, 2018; Buchmann et al., 2020; Lesourd et al., 2016).
511 For example, mechanical puzzles have been assessed without choice (Ochipa et al., 1992) but
512 also with choice, by coding tool selection and tool application separately (Bozeat et al., 2002).
513 For the sake of clarity, we grouped both choice conditions and selection scores into a broad

514 “choice condition” category, but no-choice conditions and manipulation scores into a broad
515 “no-choice category”. The number of foils also varied across studies: in the Novel Tool Test,
516 patients have to select one of three novel tools (e.g., Bozeat et al., 2002; Hodges et al., 2000;
517 Spatt et al., 2002). In the non-conventional use of familiar tools test, an array of five tools is
518 presented (Derouesné et al., 2000; Ochipa et al., 1992). In the mechanical puzzles test, one to
519 four tools have been presented in different studies (Bozeat et al., 2002; Ochipa et al., 1992). In
520 the MPS test, eight tools are given to the patient (Baumard et al., 2016, 2018; Lesourd et al.,
521 2016).

522 The precision of coding systems varied as well. Most studies have used raw accuracy-
523 based scores, leading to ceiling effects – a critical issue in the field of apraxia. Indeed, most
524 physical understanding tests are solved quite easily by healthy controls. To overcome this
525 problem, Lesourd et al. (2016) and Baumard et al. (2018) have reported time-based composite
526 scores, but on the other hand, it makes the task more sensitive to cognitive or motor
527 symptoms that may not be related directly to physical understanding (e.g., motor impairments
528 may slow down the performance even though the comprehension of mechanical actions is
529 spared).

530 Finally, Table 2 shows that different tests of physical understanding may yield different
531 results even in one and the same clinical population (e.g., the Novel Tool Test in AD). It is, for
532 the time being, not possible to explain these variations because of variations of inclusion
533 criteria as well. Diagnostic criteria keep evolving over time, thus different studies have
534 included patients based on slightly different diagnostic criteria, meaning that patients from the
535 same clinical population may actually correspond to different clinical phenotypes. For
536 example, Spatt et al. (2002) included CBS patients with diffuse cognitive impairments

537 (MMSE = 15/30) while Baumard et al. (2016) selected CBS patients with relatively isolated
538 motor impairments (MMSE 24/30).

539 **3.1.4. Data analysis**

540 This methodological discrepancy does not allow direct comparison of different studies.
541 Since different tests, conditions, and coding systems have been used, interpreting raw
542 patients' scores would be vain. So, following the method used by our research group in
543 previous studies (Baumard et al., 2014; Lesourd et al., 2013), we calculated the difference
544 between the mean controls' score and the patients' score ($M_{\text{control}} - M_{\text{patient}}$). This method
545 allows to control, in part, for intrinsic task difficulty (e.g., a score of 80/100 does not have the
546 same meaning if the healthy control sample has a score of 81, or of 99). All but one study
547 (Hodges et al., 1999) reported normative data. In some studies, only the range of scores was
548 available as normative data (Buchmann et al., 2020; Spatt et al., 2002). To avoid excluding
549 these studies from an already small study sample, we considered the mean of the minimum
550 and maximum scores as the mean score of healthy controls. There was no min-max difference
551 larger than 10% in healthy control samples, so this method was considered acceptable to give
552 an overview of patients' physical understanding impairments – in counterpart, in Figure 3
553 these studies are illustrative at most.

554 We displayed the findings in two different ways so as to give a full picture of the data.
555 First, in order to create Figure 3, we calculated Michelson contrasts as follows: (Control mean
556 – Patient mean) / (Control mean + Patient mean). With this method, the difference score
557 ranges from -1 to +1 and is scaled with respect to the sum of mean scores across groups; the
558 higher the value, the higher the control-patient difference. Second, Figure 4 displays raw
559 control-patient differences, and Table 2 displays control-patient differences weighted by

560 sample size in order to avoid over-representing small samples. We used this second method so
561 as to make our findings comparable to previous ones in Figure 4 (Osiurak & Reynaud, 2020).

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567 **Table 1. Studies of physical understanding and dementia**

Study	Population	N	Mean age	MMSE	Control group	Physical understanding		Familiar tool use	
						Task	Conditions	Task	Conditions
Thornbury et al. (1992)	AD	30	71	NA	Yes	Piagetian scales	–	–	–
Matteson et al. (1996)	Dementia*	57	77	12.7 (11.4)	No	Piagetian scales	–	–	–
Emery & Breslau (1987)	AD	25	78	Mild to severe dementia	Yes	Piagetian scales	–	–	–
	Early onset AD	14	56				–	–	–
Ochipa et al. (1992)	AD	32	73	13 (4-23)	Yes	Alternative tool selection test	Choice	Real tool use	Choice
Derouesné et al. (2002)	AD	22	70	20 (3.9; 12-25)	Yes	Mechanical puzzles	No choice	–	–
						Alternative tool selection	Choice	Real tool use	Choice & No choice
Hodges et al. (1999)	SD	2	64	–	No	Novel Tool Test	Choice	Real tool use	No choice
	CBS	1	75	–	No	Novel Tool Test	Choice		
Hodges et al. (2000)	SD	9	–	16 (7; 6-25)	Yes	Novel Tool Test	Choice & No choice	Single tool use	Considered a Choice condition
Bozeat et al. (2002)	SD	8	64	17 (9; 7-30)	Yes	Novel Tool Test	Choice & No choice	Single tool use	Considered a Choice condition
						Mechanical puzzles	Choice & No choice		
Spatt et al. (2002)	CBS	5	68	15 (7; 7-26)	Yes	Novel Tool Test	Choice & No choice	Real tool use	No choice
Lesourd et al. (2016)	AD	31	77	20 (3)	Yes	Mechanical problem-solving test; analysis of strategies	Choice & No choice	Real tool use	No choice
	SD	15	67	23 (5)	Yes				
Baumard et al. (2016)	AD	31	77	20 (11-26)	Yes	Mechanical problem-solving test (time-based scores)	Choice & No choice	Real tool use	Choice & No choice
	SD	16	67	23	Yes				
	CBS	7	71	22	Yes				
Baumard et al. (2018)	AD	32	75	20	Yes	Mechanical problem-solving test (raw scores)	Choice	Real tool use	Choice
	SD	16	67	–	Yes				
	CBS	9	70	–	Yes				
Buchmann et al. (2020)	AD + vascular dementia	27	82	17 (9-26)	Yes	Novel Tool Test	Choice & No choice (mixed score)	Real tool use	Choice & No choice (mixed score)

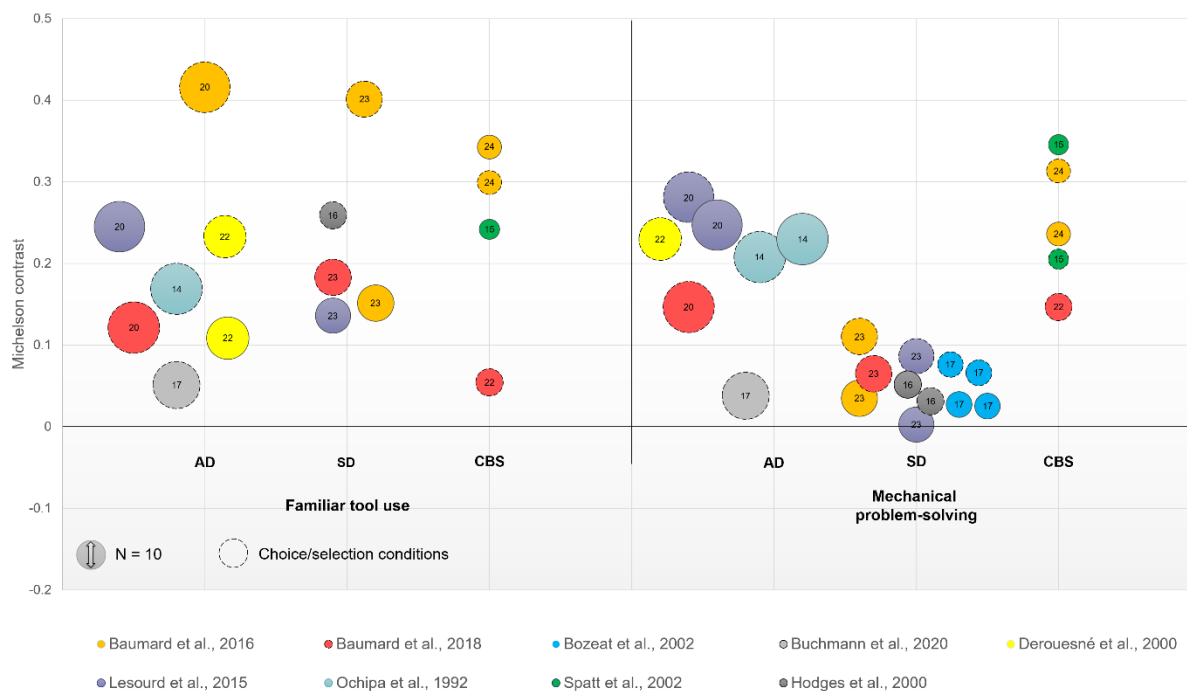
568 * Nursing home residents with cognitive impairments, including patients with Alzheimer’s disease and related disorders, but also with acute conditions like stroke or heart
 569 disease. AD: Alzheimer’s disease; SD: Semantic dementia; CBS: Corticobasal syndrome. Values between brackets are standard deviations and min-max ranges.

570

571 **Table 2. Performance on tests of physical understanding and familiar tool use.**

Study	Sample size				Familiar tool use				Non-conventional use of familiar tools				Novel tool test				Mechanical puzzles				Mechanical problem-solving test						
	HC	AD	SD	CBS	HC	AD	SD	CBS	HC	AD	SD	CBS	HC	AD	SD	CBS	HC	AD	SD	CBS	HC	AD	SD	CBS			
Ochipa et al. (1992)	32	32	–	–	100	71.1	–	–	89.8	58.9	–	–	–	–	–	–	<u>92.2</u>	<u>60.1</u>	–	–	–	–	–	–			
Derouesné et al. (2000)	10	22	–	–	98	61	–	–	99	62	–	–	–	–	–	–	–	–	–	–	–	–	–	–			
	–	–	–	–	<u>97</u>	<u>78</u>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–			
Hodges et al. (1999) ^a	–	–	2	1	–	–	<u>42</u>	<u>59.5</u>	–	–	–	–	–	–	100	58	–	–	–	–	–	–	–	–			
Hodges et al. (2000) ^{a,b}	8	–	9	–	91.9 ^f	–	54.1 ^f	–	–	–	–	–	–	97.6	–	91.7	–	–	–	–	–	–	–	–			
	–	–	–	–	–	–	–	–	–	–	–	–	–	<u>99</u>	–	89.3	–	–	–	–	–	–	–	–			
Bozeat et al. (2002) ^b	10	–	8	–	–	–	62.9 ^f	–	–	–	–	–	–	97.7	–	85.6	–	77.7	–	66.7	–	–	–	–			
	–	–	–	–	–	–	72.7	–	–	–	–	–	–	<u>99.5</u>	–	94.6	–	<u>97.9</u>	–	92.7	–	–	–	–			
Spatt et al. (2002)	5	–	–	5	<u>90-100</u>	–	–	<u>58</u>	–	–	–	–	–	92-100	–	–	63.3	–	–	–	–	–	–	–			
	–	–	–	–	–	–	–	–	–	–	–	–	–	<u>92-100</u>	–	–	<u>46.7</u>	–	–	–	–	–	–	–			
Lesourd et al. (2016) ^c	31	31	15	–	<u>63.5</u>	<u>38.5</u>	<u>48.3</u>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	54.7	30.7	46.0	–	
	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	<u>56.3</u>	<u>34</u>	<u>56</u>	–	
Baumard et al. (2016) ^{c,d}	31	31	16	7	60.6	25	25.9	32.7	–	–	–	–	–	–	–	–	–	–	–	–	–	–	54.7	30.7	43.8	28.6	
	–	–	–	–	<u>63.5</u>	<u>38.5</u>	<u>46.8</u>	<u>31.1</u>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	<u>56.3</u>	<u>34</u>	<u>52.5</u>	<u>34.8</u>
Baumard et al. (2018) ^d	32	32	16	9	97	76	67	87	–	–	–	–	–	–	–	–	–	–	–	–	–	–	91.1	67.8	80.0	67.8	
Buchmann et al. (2020) ^e	82	27	–	–	93.8 ^g	84.7	–	–	–	–	–	–	–	73.8 ^g	68.4	–	–	–	–	–	–	–	–	–	–	–	
Mean	–	–	–	–	86.0	59.1	52.5	53.7	94.4	60.5	–	–	–	94.2	68.4	92.2	56.0	89.3	60.1	79.7	–	–	–	62.6	39.4	55.7	43.7
Mean (weighted by sample sizes)	–	–	–	–	84.4	58.0	51.3	54.5	92.0	60.2	–	–	–	82.5	68.4	90.9	55.3	90.5	60.1	79.7	–	–	–	62.8	39.6	55.8	45.8
Mean control-patient difference	–	–	–	–	–	25.1	26.9	26.8	–	34.0	–	–	–	–	5.4	8.2	41.0	–	32.1	8.1	–	–	–	–	23.2	7.0	23.6
Mean control-patient difference (weighted by sample sizes)	–	–	–	–	–	25.1	26.0	24.9	–	33.4	–	–	–	–	5.4	8.1	41.0	–	32.1	8.1	–	–	–	–	23.2	7.0	23.6

572 *Notes.* Values are mean scores obtained by healthy controls (HC), or patients with Alzheimer’s disease (AD), semantic dementia (SD), or corticobasal syndrome (CBS). With
573 the exception of the lower lines, bolded values are non-significant control/patient differences. Underlined values correspond to no-choice conditions, in which the patients had
574 to manipulate, but not to select tools. Sample overlap: ^a 22%, ^b 22%, ^c 85%, ^d 96%. Of note, Baumard et al. (2016) used a time-based composite score to avoid ceiling effects in
575 the healthy control group, while Baumard et al. (2018) reported raw, accuracy-based scores. ^e Mixed sample of patients with Alzheimer’s disease or vascular dementia. For
576 this study, the score obtained on the Novel Tool Test mixes “selection” and “use” scores, and was therefore considered a “choice” condition. ^f This task was actually a single
577 tool use task in which patients were asked to demonstrate the use of a tool while holding it in hand, but without the corresponding recipient object. It was considered a choice
578 condition because patients have to select possible target objects from memory, a task requirement that has been associated with semantic memory (Baumard et al., 2016). ^g
579 Normative data retrieved from Buchmann et al., 2017: only the cut-off scores were available so the impairment of AD patients may be underestimated in this table as well as
580 in Figure 3.



581

582 **Figure 3. Control-patient difference in familiar tool use and mechanical problem-solving tests.** The Y-axis
 583 displays Michelson contrast (range -1 to 1); the higher the value, the higher the control patient difference. The
 584 diameter of circles shows the sample size. Dotted lines correspond to either choice conditions (i.e., the
 585 participant has to select and manipulate a tool) or selection scores (i.e., selection, but not manipulation, is coded).
 586 Values within circles correspond to the mean MMSE score of the clinical sample. AD: Alzheimer’s disease. SD:
 587 Semantic dementia. CBS: Corticobasal syndrome. Of note, Buchmann et al. (2020), the lower value for AD, used
 588 a score combining “selection” and “use” scores, and only the cut-off scores were available as normative data,
 589 meaning that the control-patient difference reported in this figure is an underestimation of the actual deficit.

590

591 **3.2. Do patients with dementia have deficits of physical**
 592 **understanding?**

593 The following section will describe the current state of the art for each syndrome
 594 separately. Table 2 and Figure 3 provide an overview of the findings.

595 **3.2.1. Alzheimer’s disease**

596 Alzheimer’s disease (McKhann et al., 2011) is characterized by a progressive cortical
 597 atrophy of the medial, basal and lateral temporal lobe, as well as of the parietal lobe. Frontal

598 variants have also been described (Lam et al., 2013). The clinical presentation includes
599 progressive, insidious worsening of cognitive functions that interferes with usual activities of
600 daily living. The most prominent clinical impairments may regard not only episodic memory
601 (i.e., the amnesic form of AD), but also language, semantic memory, visuospatial skills, or
602 executive dysfunction. Apraxia has also been consistently reported (for a review see Lesourd
603 et al., 2013). The evolution of the disease over years always converges toward a general
604 cognitive deterioration, meaning that clinical dissociations are obvious only in the first years
605 of evolution. Given this clinical heterogeneity, the label “Alzheimer’s disease” may
606 correspond to very different cognitive profiles, an issue that is even more complex
607 considering the evolution of diagnostic criteria over time. The common point between all
608 profiles, that said, is the progressive decline of the ability to interact with everyday tools and
609 objects, as documented by clinical inventories (e.g., instrumental activities of daily living;
610 Lawton & Brody, 1969).

611 To our knowledge, the first studies on physical understanding in AD used Piagetian
612 paradigms. Thornbury et al. (1992) have found that healthy adults obtained scores
613 corresponding to the concrete operational development stage (the highest stage in this study),
614 whereas 50% of AD patients obtained scores corresponding to less mature developmental
615 stages (sensorimotor stage characterized by a performance based on mental habits, imitation,
616 and rudimentary trial and error strategies, 17%; preoperational stage characterized by
617 egocentric thought and lack of abstraction, 33%). About a third of the patients failed mass,
618 liquid, or surface conservation tests. Matteson et al. (1996) found similar results, albeit with
619 lower methodological control (i.e., sample mixing Alzheimer and stroke patients; no control
620 group). Using a taxonomy that is now outdated, Emery and Breslau (1987) compared “senile”
621 (age-related) AD, and early onset AD on conservation tests, both groups including patients

622 with mild to severe dementia. They found impaired and similar performance in both groups
623 (respectively, 19.2% and 15.8% of the maximum score, against 58.0% for healthy controls).

624 Physical understanding has been more extensively explored in the apraxia literature. All
625 the studies carried out on AD have found significant impairments, with control-patient
626 differences ranging from 5 to 33% (Table 2). There is no effect of choice/no-choice conditions
627 (choice condition 5 to 37%%; no-choice condition 22 to 32%). The Novel Tool Test seems to
628 be far easier than other tests (Buchmann et al., 2020). This may be because this study reported
629 cut-off scores only, while it might also indicate that mechanical problem-solving tasks relying
630 on perceptual judgments are easier to AD patients than tasks putting heavier loads on physical
631 judgments. Matching shapes is actually closer to tests of agnosia, a syndrome that is not
632 typical of AD except in late stages. This conclusion, however, remains to be confirmed by
633 additional studies, especially since Buchmann et al. included patients with AD or vascular
634 dementia in one and the same sample, making this study hard to compare to others. In
635 contrast, other physical understanding tests have yielded very similar levels of impairment.
636 Ochipa et al. (1992) used mechanical puzzles, and found that AD patients had lower
637 performance than healthy controls. The same was found by studies on the non-conventional
638 use of familiar tools (Ochipa et al., 1992; Derouesné et al., 2000). The latter task is the most
639 difficult one, which might indicate that inhibiting the conventional use of objects adds an
640 additional layer of difficulty to physical understanding tests for some patients. To sum up this
641 section, patients with Alzheimer's disease do have difficulties selecting and manipulating
642 novel tools to solve mechanical problems, albeit with possible task-dependent effects (e.g.,
643 visual/spatial versus technical problem-solving).

644 **3.2.2. Semantic dementia**

645 Semantic dementia is a focal cortical atrophy syndrome characterized by progressive
646 loss of semantic knowledge, associated with cortical atrophy circumscribed to the ventral and
647 polar parts of the temporal lobes (Galton et al., 2001). This loss of knowledge can be
648 demonstrated in the domains of language (e.g., loss of word meaning, comprehension
649 impairments), and perception (e.g., loss of knowledge about the conventional function of tools
650 and objects; Bozeat et al., 2002; Bozeat et al., 2000; Gorno-Tempini et al., 2011; Hodges et
651 al., 1999, 2000; Neary et al., 1998). Typically, it dominates the clinical picture for years
652 before other cognitive impairments can be observed. This syndrome is therefore a relevant
653 clinical model to study normal cognitive functioning, minus semantic tool knowledge.

654 There is remarkable consistency in the literature showing that SD patients have normal
655 performance in tests of physical understanding, with control-patient differences ranging from
656 7% with the Mechanical Problem-Solving test, to 8% with the Mechanical Puzzles and Novel
657 Tool Tests (Table 2, Figure 3). As in AD patients, there is no clear effect of choice (control-
658 patient difference: choice condition 8 to 12%; no-choice condition 0 to 10%). Of note, there is
659 only little overlap between the performance of AD and SD patients (AD: 5-33%; SD: 7-8%),
660 confirming that the performance of AD patients is disease-specific and not explainable by the
661 mere presence of brain lesions – an assumption confirmed by the comparison of dementia
662 with traumatic brain injury or multiple sclerosis (Buchmann et al., 2020). Using the Novel
663 Tool Test, Hodges et al. (1999) were the first to demonstrate, in two cases, that patients may
664 still solve mechanical problems in the context of severe semantic loss. They replicated this
665 observation in a larger sample and found that the patients performed at ceiling, with flawless
666 performance (Hodges et al., 2000). Bozeat et al. (2002) additionally demonstrated that their
667 performance was normal with mechanical puzzles as the ones used by Ochipa et al. (1992).
668 This has suggested that their normal performance was not problem-dependent, but rather due
669 to the preservation of physical understanding. Interestingly, Hodges et al. (1999) had

670 described the reverse profile in a patient with corticobasal syndrome, what Baumard et al.
671 (2016) later confirmed in a group study. In the latter, only 12% of SD cases showed a deficit.
672 To sum up, the now well accepted dissociation in SD between physical understanding on the
673 one hand, and semantic tool knowledge on the other hand, is in line with the core assumptions
674 of the 4CT (Osiurak, 2014), as well as with McCloskey's (1983) first finding that explicit
675 knowledge is not a sufficient condition to interact with the physical world.

676 **3.2.3. Corticobasal syndrome**

677 Corticobasal syndrome is an atypical parkinsonian syndrome characterized by brain
678 atrophy in both the basal ganglia, and frontal-parietal cortical areas. The clinical picture
679 combines elementary motor symptoms (e.g., limb rigidity, akinesia, dystonia, myoclonus)
680 with sensory deficits (i.e., tact, proprioception) and higher-order cognitive impairments (e.g.,
681 apraxia; Armstrong et al., 2013; Litvan et al., 1997). The corticobasal "syndrome" label is
682 preferred to the corticobasal "degeneration" label in clinical studies without post-mortem
683 confirmation of the underlying pathology (Shelley et al., 2009).

684 Only four studies have investigated mechanical problem-solving skills in this
685 population, yielding a control-patient difference of 23% to 41%. Spatt et al. (2002) used the
686 Novel Tool Test, and found that all of five cases had impaired performance. The patients
687 failed not only to manipulate the tools, but also to select them, leading Spatt et al. to conclude
688 that motor dysfunction could not explain this finding. Baumard et al. (2016) found that CBS
689 patients performed lower than controls in the MPS test. About 70% of cases failed at least one
690 of the two conditions (i.e., choice, no-choice). Nevertheless, the frequency of physical
691 understanding deficits in this population does not make consensus (22 to 100% of cases
692 depending on studies). Contrary to what was found in other clinical groups, no-choice
693 conditions may be slightly more difficult than choice conditions (control-patient difference:

694 choice condition 23 to 32%; no-choice condition 21 to 49%). This depends on the coding
695 systems used. Baumard et al. (2016) used a coding system capturing both selection and
696 manipulation in the choice condition, but only manipulation in the no-choice condition; they
697 found that the choice condition (C-P difference: 26.1%) was as difficult as the no-choice
698 condition (C-P difference: 21.5%). By coding separately tool selection and tool manipulation
699 in one and the same choice condition, Spatt et al. (2002) found that tool manipulation (C-P
700 difference: 49.3%) was actually more difficult for these patients than tool selection (C-P
701 difference: 32.7%). So, the core deficit in CBS patients is probably not a tool selection deficit,
702 but rather a tool manipulation deficit. This questions the actual existence of a deficit of
703 physical understanding in this population, because the latter should be associated with tool
704 selection deficits – an issue to be discussed in further sections.

705 **3.3. Does physical understanding predict familiar tool use skills?**

706 Studies on stroke patients have demonstrated a strong relation between tests of physical
707 understanding, and familiar tool use (Baumard et al., 2014; Osiurak & Reynaud, 2020). From
708 Table 2 and Figure 3, it is clear that each of the three groups of interest demonstrate impaired
709 use of familiar tools. The latter, however, may depend on multiple cognitive processes, and
710 not only on physical understanding. So, this section discusses whether physical understanding
711 may accurately predict familiar tool use. Figure 4 displays the association between control-
712 patient difference scores for familiar tool use and for mechanical problem-solving tests, all
713 patient groups, tasks and conditions combined, using the same method as in stroke studies
714 (Osiurak & Reynaud, 2020). Figure 4 has two panels. The left panel corresponds to stroke
715 studies only, and the figure has been extracted from Osiurak et Reynaud's (2020) study. The
716 right panel is the analysis we performed in the present study, and it corresponds to patients
717 with neurodegenerative diseases. Control-patient differences could be calculated for familiar
718 tool use in 8 studies (see Table 2; Ochipa et al., 1992; Derouesné et al., 2000 ; Hodges et al.,

719 2000 ; Spatt et al., 2002 ; Lesourd et al., 2015 ; Baumard et al., 2016 ; Baumard et al., 2018 ;
720 Buchmann et al., 2020). We removed two studies (Lesourd et al., 2015; Baumard et al., 2018)
721 to avoid sample overlap. The analysis in Figure 4 (right panel) is therefore based on six
722 studies. While the comparison is illustrative at most with such a limited dataset, the
723 correlation seems weaker in patients with neurodegenerative diseases than in patients with
724 stroke (Osiurak & Reynaud, 2020), especially if one considers the weight of Buchmann et
725 al.'s (2020) study (see peculiarities of this study above and in the captions of figures and
726 tables). This is probably because of the specific nature of brain lesions and cognitive
727 dysfunction in neurodegenerative diseases – a less homogeneous clinical group than left-
728 hemisphere stroke patient groups.

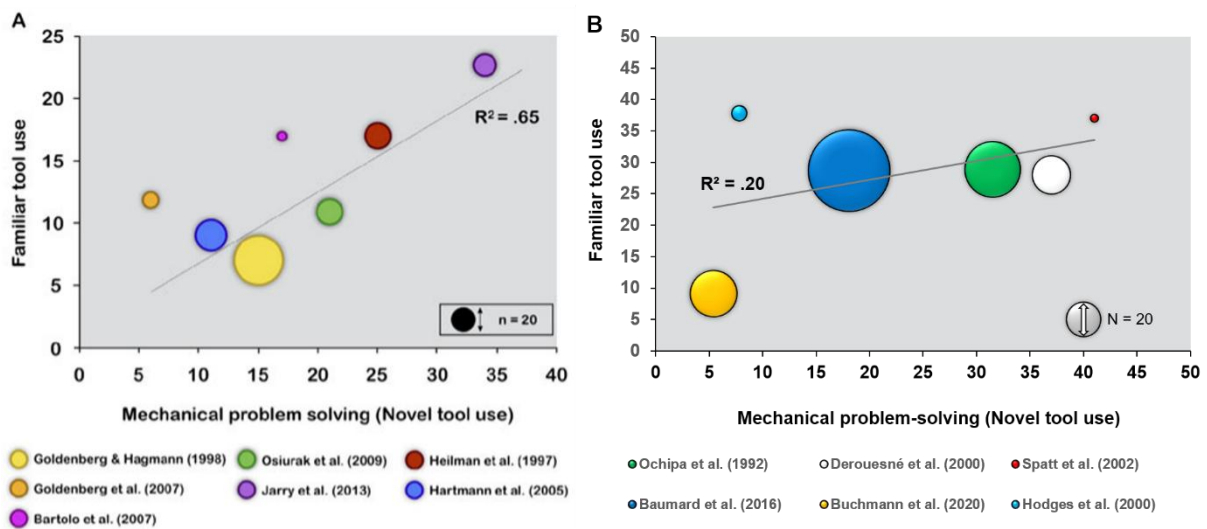
729 Patients with AD show relatively similar levels of performance in tests of physical
730 understanding and familiar tool use, with only limited effect of choice (familiar tool use:
731 choice condition 9 to 37%; no-choice condition 19 to 25%). Derouesné et al. (2000) found
732 that the performance on different tool use tests, including the alternative tool selection test,
733 was a good predictor of the performance in activities of daily living. In the studies by
734 Baumard et al. (2016, 2018), 44 to 65% of AD patients failed mechanical problem-solving
735 tests, and 71 to 89% of these cases failed to use familiar tools properly. Taken together,
736 physical understanding and semantic tool knowledge were good predictors of the overall
737 familiar tool use performance. We performed the same regression as the one displayed in
738 Figure 4, based on Alzheimer studies only (Ochipa et al., 1992; Derouesné et al., 2000;
739 Baumard et al., 2016; Buchmann et al., 2020). We found a positive association between both
740 tests ($R^2 = .75$; or $R^2 = .81$ considering choice conditions only). On this ground, one could
741 assume that the performance on tests assessing physical understanding predicts well the
742 performance on familiar tool use tests. It should be acknowledged, however, that one study

743 (Buchmann et al., 2020) highly influenced the correlation (see Supplementary Figure 1), so
744 future studies are needed to confirm this association.

745 Patients with semantic dementia show the most marked dissociation between severely
746 impaired familiar tool use skills, and normal physical understanding (Table 2, Figure 3). In
747 these patients, the loss of semantic tool knowledge explains well familiar tool use deficits.
748 From Figure 3, the need to select tools seems to have an impact on control-patient differences.
749 In particular, Baumard et al. (2016) found a positive correlation between tool selection
750 deficits and semantic tool knowledge deficits. In this study, the performance dramatically
751 improved when patients were asked to manipulate, but not to select familiar tools. In other
752 words, patients cannot select the tool that the examiner expects, because it would require
753 access to conventional, semantic tool knowledge, but they still can select tools, infer their
754 possible function, and use them based on physical understanding (Osiurak, Aubin, Allain,
755 Jarry, Richard, et al., 2008). No-choice conditions, in contrast, put only little loads on
756 semantic tool knowledge, because in that case physical understanding alone may compensate
757 for the semantic loss, especially when tool-object mechanical complementarity is transparent
758 (Bozeat et al., 2002; Hartmann et al., 2005). For example, even if the patient no longer knows
759 the function of a bottle-opener, she/he may infer its proper use by analyzing the mechanical
760 properties offered by both the bottle and the bottle-opener. Finally, this may explain
761 dissociations (1) between impaired familiar tool use and normal physical understanding; (2)
762 between the choice and no-choice conditions of familiar tool use. The preservation of physical
763 understanding in the context of semantic loss may explain the unique profile of performance
764 of SD patients.

765 Interestingly, patients with CBS show different, if not reverse patterns of performance.
766 As was the case for tests of physical understanding, the no-choice condition of familiar tool
767 use may be more difficult than the choice condition (control-patient difference: choice

768 condition 10 to 37%; no-choice condition 32%; see also Figure 3), a dissociation found only
 769 in the CBS group. This suggests that semantic tool knowledge is not a relevant predictor of
 770 familiar tool use in this group. Physical understanding is impaired in up to 100% of CBS
 771 cases depending on coding systems, and 50 to 100% of these cases show impaired familiar
 772 tool use (Baumard et al., 2016, 2018; Spatt et al., 2002). On this ground, the performance on
 773 tests of physical understanding may seem a good predictor of familiar tool use skills. This
 774 assumption, however, calls for further confirmation because only two small cohorts have been
 775 described, with substantial methodological discrepancy.



776

777 **Figure 4. Associations between familiar tool use and mechanical problem-solving skills.** Each circle is a
 778 study, and the diameter of circles corresponds to sample sizes. Values correspond to control-patient differences.
 779 Left panel: performance of patients with left hemispheric stroke, as displayed by Osiurak & Reynaud (2020),
 780 showing a strong association between physical understanding and familiar tool use. Right panel: performance of
 781 patients with neurodegenerative diseases, showing a weaker association. We used the mean score of all tests (i.e.,
 782 unconventional use of familiar tools, mechanical puzzles, novel tool test, mechanical problem-solving test) and
 783 conditions (i.e., choice Vs. no-choice). For the only one study with several clinical groups (Baumard et al.,
 784 2016), the mean of the whole patient sample was used. Studies with large overlap were not included to avoid
 785 over-representing the data from these studies. The R^2 value is highly influenced by Buchmann et al.'s study since
 786 removing this study makes the R^2 fall down to $R^2 = .06$. This suggests that other cognitive dimensions than
 787 physical understanding contribute to familiar tool use.

788

789 **3.4. Is physical understanding really impaired in neurodegenerative**
 790 **diseases?**

791 The fact that the performance in tests of physical understanding predicts the
792 performance in familiar tool use tests, does not mean that physical understanding itself is the
793 (only) predictor. Presumably, mechanical problem-solving tests engage not only physical
794 understanding, but also motor functions for the actual manipulation of tools, episodic memory
795 to retain the instructions, and executive functions to deal with the problem's novelty. Even
796 though stroke studies have clearly demonstrated the autonomy of physical understanding
797 toward motor and executive functions (Goldenberg & Hagmann, 1998; Goldenberg et al.,
798 2007; Hartmann et al., 2005; Liepmann, 1905, 1920;), little is known as to how these
799 functions may interact during mechanical problem-solving by patients with neurodegenerative
800 diseases. Lesourd et al. (2016) found that working and episodic memory scores were good
801 predictors of the performance on the mechanical problem-solving test. Baumard et al. (2018)
802 explored the weight of these dimensions. They found 1) that 47% of AD patients (but 7% and
803 22% of SD and CBS patients) failed a modified version of the Tower of London test assessing
804 planning skills (Jarry et al., 2013); 2) double dissociations between this test and mechanical
805 problem-solving; 3) a positive correlation ($r = 0.47$) between both tests. About 94% of these
806 AD patients failed to use familiar tools. In contrast, episodic memory played only a negligible
807 role. In the only qualitative study of tests of physical understanding, Lesourd et al. (2016)
808 have compared not only the performance, but also the strategy used by AD patients and
809 patients with left-hemisphere stroke (LHS; Osiurak et al., 2013). They counted the time that
810 patients spent performing tool-box interactions, a measure that was supposed to indicate the
811 underlying understanding of physical tool-box potential interactions. While both AD and LHS
812 patients failed the test, only LHS patients had abnormal strategies (i.e., less tool-box
813 interactions). This is also consistent with the fact that LHS patients, but not early-stage AD
814 patients, commit severe tool use errors revealing misconception about physical interactions.
815 In summary, patients with AD do have problem-solving deficits, but based on the current state

816 of the literature, it seems improbable that it may reflect actual deficits of physical
817 understanding in all patients. As previously emphasized by Lesourd et al. (2016), apraxia of
818 tool use may not be of the same nature in LHS and AD patients. Patients with acute left
819 hemisphere stroke generally demonstrate “true” deficits of physical understanding, whereas
820 patients with AD have unspecific, yet sometimes multiple cognitive deficits that may
821 secondarily hamper the use of familiar and novel tools (at least in the first stages of the
822 disease, as we will argue in the next section). It is also quite plausible that some patients fail
823 to solve mechanical problems not because of physical understanding deficits but rather
824 because of either early sensory/attentional processing deficits (preventing patients from
825 extracting useful information about the physical world), or mental simulation deficits
826 (preventing them from predicting how different materials may interact; Osiurak, 2014;
827 Battaglia et al., 2013).

828 As regards the CBS group, Baumard et al. (2018) found a strong and positive
829 association ($r = 0.98$) between performance in the MPS test, and performance in a test
830 assessing fine motor dexterity. In fact, CBS patients had abnormal time-based composite
831 scores (82% of patients showed a deficit), but better accuracy-based scores (22% of patients
832 showed a deficit; Baumard et al., 2016, 2018). This, along with the higher performance in
833 choice than in no-choice conditions, suggests that CBS patients had mainly motor production
834 deficits, preventing them from manipulating novel tools, while true deficits of physical
835 understanding were rare. On this ground, future works should probably assess physical
836 understanding while controlling for tool manipulation, as did Lesourd et al. (2017) in stroke
837 patients, and test the whole cognition.

838 **3.5. What is the effect of global cognitive deterioration?**

839 Whether AD or CBS patients have deficits of physical understanding probably is a
840 function of the stage of the disease. Piagetian studies found erroneous physical judgments in
841 (sometimes institutionalized) patients with moderate to severe dementia (Emery & Breslau,
842 1987) or advanced cognitive deterioration (mean MMSE 12.7, standard deviation 11.4). These
843 patients showed “severe” impairments of physical understanding, in that they failed to
844 understand elementary conservation and reversibility laws that are acquired early in life. In
845 Thornbury et al.’s (1992) study, the impairment was correlated to the severity of the disease as
846 reflected by the MMSE score. Emerey and Breslau (1987) found that after controlling for
847 dementia severity, the duration of time since onset was a good predictor of performance on
848 conservation paradigms, in particular in patients with early onset AD. It is noteworthy that
849 these studies have included patients that might correspond to other neurodegenerative
850 diseases that were included in clinical taxonomies few years later (e.g., frontotemporal lobar
851 degeneration, Neary et al., 1998; posterior cortical atrophy, Benson et al., 1988). Conservation
852 paradigms have not been used with reference to updated AD taxonomies (McKhann et al.,
853 2011).

854 In comparison, more recent studies have included patients with higher MMSE scores.
855 As shown in Figure 3, patient groups with MMSE scores ranging from 14 to 22 showed
856 similar levels of impairment in tests of physical understanding. These studies have led us to
857 conclude that AD patients have mechanical problem-solving deficits, but probably not “true”
858 physical understanding deficits (see section 3.4). They have also showed that the performance
859 in tests of physical understanding was not well predicted by general cognitive deterioration
860 (Derouesné et al., 2002). Therefore, there is probably a shift, with the evolution of the disease,
861 in the comprehension that patients have of the physical world. We assume that physical
862 understanding does decay over time (there is actually no reason why the left area PF should
863 resist more than other brain regions to the progression of cortical atrophy), yet this

864 deterioration probably occurs in late stages of the evolution, in patients with moderate to
865 severe dementia. Such deficits probably induce more general cognitive deficits and hence
866 significant loss of autonomy, in that physical understanding has been proposed to ground
867 higher cognition (e.g., forming concepts and goals, talking about the world, detecting
868 situations demanding special attention; Battaglia et al., 2013). In other words, functional
869 autonomy probably goes through three phases: 1) Pre-clinical stage: normal tool-related
870 cognitive mechanisms (i.e., physical understanding, executive functions, semantic tool
871 knowledge, motor simulation); 2) Clinical stage: patients may have difficulties to use familiar
872 tools under some circumstances because of associated cognitive deficits (e.g., executive
873 dysfunction may hamper novel or multi-step activities; semantic memory loss may prevent
874 patients from using tools in a conventional way), yet physical understanding is spared. As a
875 result, patients may show good residual tool use skills, and hence functional autonomy
876 remains relatively spared; 3) Functional dependence: physical understanding is altered,
877 causing severe loss of autonomy and leading to institutionalization.

878 A similar rationale may apply to CBS patients. Spatt et al. (2002) included patients with
879 widespread cognitive impairments (mean MMSE = 15; language, semantic, and visual-spatial
880 impairments), whereas Baumard et al. (2016, 2017) included patients with relatively isolated
881 motor deficits (mean MMSE = 24 and 22, respectively). As a matter of fact, Spatt et al.
882 reported more severe physical understanding impairments than Baumard et al. So, CBS
883 patients with diffuse cognitive impairments (whether because of longer evolution, or due to
884 particular patterns of atrophy and clinical presentations) have shown more severe impairments
885 on physical understanding tests than CBS patients with isolated motor deficits. Future studies
886 are needed to confirm the predictive value of physical understanding deficits for health care
887 decisions.

888

4. CONCLUDING REMARKS AND FUTURE DIRECTIONS

889 Over the years, neurological studies have emphasized the importance of assessing
890 physical understanding, especially in the light of positive correlations between these skills and
891 the ability to use familiar tools in a more ecological context (Osiurak & Reynaud, 2020).
892 Based on the current literature, three conclusions can be drawn. First, patients with AD do
893 have mechanical problem-solving deficits. Executive dysfunction may account for the latter,
894 at least in the first stages of the disease, while the clinical picture may later evolve toward
895 more specific, and probably more disabling physical understanding deficits. Longitudinal
896 studies could better document the course of the disease in this regard. Second, CBS patients
897 suffer mainly from tool manipulation deficits associated with motor disorders, even though
898 deficits of physical understanding cannot be excluded in patients with more widespread
899 cognitive impairments. Third, the loss of semantic tool knowledge, as the one documented in
900 semantic dementia, does not prevent patients from solving mechanical problems. This is in
901 line with the previously documented dissociation between pragmatic, physical understanding
902 supported by the left inferior parietal lobe, and decontextualized, explicit knowledge
903 supported by the temporal lobes.

904 Surprisingly, however, the literature on novel tool use remains sparse, and there has
905 been no study using intuitive physics paradigms in patients with dementia. Since these
906 patients show relatively specific cognitive impairments, documenting associations and
907 dissociations between familiar tool use and different paradigms of physical understanding
908 may be of great interest. This could help to improve neuropsychological evaluations, but also
909 to implement new, disease-specific care strategies. Assuming that some human-tool
910 interactions may not rely on physical understanding (e.g., reach and grasp movements, simple
911 predictions regarding moving objects) may help better analyze some patients' residual tool

912 use skills. After all, apes are capable of causal reasoning when tools are not involved (Vaesen,
913 2012). Whether impairments of physical understanding, in isolation or associated with other
914 cognitive deficits, accurately predict particular error types in familiar tool use tasks, as well as
915 the functional outcome, deserves further studies. Some questionnaires may be of use in this
916 regard (e.g., Force Concept Inventory, Hestenes et al., 1992). It is also important for future
917 studies to make available the performance of individual cases, and not only group-level
918 values, because the latter may overlook between- task dissociations in individual patients
919 (Caramazza, 1986; Negri et al., 2007). This will allow studying potential dissociations
920 between different tool use conditions and tests of physical understanding, and hence deriving
921 inferences on possible fractionations of the physical engine.

922 This review has some limitations. First, there has been substantial overlap between
923 some studies, thus the generalization of the findings has only limited scope. Second,
924 diagnostic criteria have considerably evolved over years, meaning that studies conducted in
925 the 90's are not fully comparable to studies conducted in the 2010's. Since taxonomies are
926 likely to evolve in future years, studies should probably not merely depict the performance of
927 clinical groups, but also provide a fine-grained analysis of cognitive profiles. This may also
928 allow to control for cognitive dimensions other than physical understanding, but that may
929 prevent patients from completing problem-solving tests (e.g., working memory, episodic
930 memory, executive functioning, visual-spatial skills). Third, most of the studies included in
931 this review could not escape a publication bias. Since studies with significant control-patient
932 differences are more easily published than studies with negative findings, the effect of
933 dementia on physical understanding might be over-estimated. For instance, when causal
934 reasoning tasks (in which participants are asked to predict the movement of an object) are
935 used as control tasks for comparison with social reasoning tasks, there is actually no
936 difference between AD patients and healthy controls (e.g., Verdon et al., 2007). It is also

937 possible that these tests are not fully equivalent to mechanical problem-solving tests. To
938 overcome this bias, future studies are encouraged to compare different clinical populations, as
939 well as different paradigms in the same population, with the intention to infer which
940 dimensions are at the root of disease-specific clinical impairments. In a “problem complexity
941 approach”, Proffitt and Gilden (1989) have made a distinction between easy and difficult
942 intuitive physics tasks, defined as a function of the number of physical dimensions of motion
943 that participants have to deal with. This may be a relevant independent or control variable in
944 future clinical studies, because it finds echo with theories of tool use considering that errors
945 arise from the interaction between task complexity and limited cognitive resources (e.g.,
946 Giovannetti et al., 2002). Fourth, we have accepted different concepts as circumstantial
947 synonyms, given both the resemblances between concepts, and the scarcity of the literature on
948 physical understanding and dementia. Yet, perhaps they are not fully superimposable: In
949 intuitive physics paradigms, the normal performance (frequent in the normal population) is to
950 make an erroneous prediction, whereas in tool use paradigms, the normal performance is
951 defined as a successful tool use action, which implies that the participant correctly used the
952 laws of physics. To our knowledge, there has been no study addressing this issue and
953 comparing different paradigms on a one-to-one basis under varying conditions (e.g.,
954 concreteness, effect of perceptual/contextual cues, number of physical dimensions; see section
955 2.1.4).

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