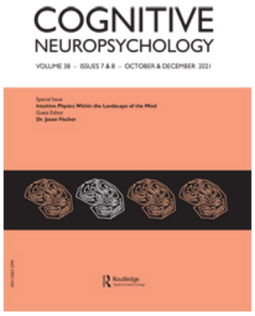

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Physical understanding in neurodegenerative diseases

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ABSTRACT
This quantitative review gives an overview of physical understanding (i.e., the ability to represent and use the laws of physics to interact with the physical world) impairments in Alzheimer's disease (AD), semantic dementia (SD), and corticobasal syndrome (CBS), as assessed mainly with mechanical problem-solving and tool use tests. This review shows that: (1) SD patients have apraxia of tool use because of semantic tool knowledge deficits, but normal performance in tests of physical understanding; (2) AD and CBS patients show impaired performance in mechanical problem-solving tests, probably not because of intrinsic deficits of physical understanding, but rather because of additional cognitive (AD) or motor impairments (CBS); (3) As a result, the performance in mechanical problem-solving tests is not a good predictor of familiar tool use in dementia; (4) Actual deficits of physical understanding are probably observed only in late stages of neurodegenerative diseases, and associated with functional loss.

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1. Introduction

Humans, like other animals, are biological entities immerged in a physical world. A fundamental issue at the edge of physics and psychology is, therefore, to understand how the laws of physics shape the human mind, and conversely, how individuals represent and use the physical laws (hereafter referred to as "physical understanding"). In an ecological context, physical understanding has been proposed to be at the root of humans' highly flexible tool use skills, tool making and analogical reasoning (e.g., anticipating that lifting a heavy object will call for more muscular strength than lifting a light object; understanding that glass is heavy and solid enough to smash a spider, but not to hammer a nail; anticipating how to grasp a tool as a function of its subsequent use; Allen et al., 2020; Goldenberg & Spatt, 2009; Goldenberg, 2009; Osiurak, 2014; Osiurak et al., 2008a, 2009, 2010, 2011; Osiurak & Reynaud, 2020; Povinelli, 2000; Vaesen, 2012). There has been evidence for a double dissociation between physical understanding ("how things work"; e.g., judging in which direction an unstable tower of blocks will fall) and psychological understanding ("how people work"; Kamps et al., 2017; Osiurak & Reynaud, 2020), suggesting that physical understanding is a specific mental ability. While the latter has long been studied by asking healthy adults to make predictions regarding physical events that are going to happen in a near future (e.g., Caramazza et al., 1981; McCloskey et al., 1980; McCloskey, 1983a, 1983b), improving our comprehension of how neurological diseases in general, and neurodegenerative diseases in particular, alter physical understanding may lead to significant breakthrough in this field (Hubbard, 2019). Studying the ecology of physical understanding may in turn help to better understand the loss of autonomy of some patients, and contribute to the differential diagnosis. The literature is, however, sparse on this topic, while there have been more studies on tool use skills. Focusing on the latter may provide insight on physical understanding, for three reasons: (1) in an ecological setting, tool use is probably the most frequent activity that would call for physical understanding (e.g., we use tools more frequently than we solve abstract physics problems); (2) some links have been

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demonstrated between tool use and physical understanding in patients with stroke; (3) to our knowledge, there is literature on how patients with dementia solve concrete tool use situations but not abstract physics problems.

It turns out that patients with dementia typically demonstrate a loss of autonomy, a diagnostic criterion of all neurodegenerative diseases (Crutch et al., 2013, 2017; Gorno-Tempini et al., 2011; McKhann et al., 2011). As a matter of fact, apraxia of tool use (i.e., the inability to properly use familiar or novel tools and objects, that cannot be explained by motor or sensory deficit, or by attentional or language impairments; Dovern et al., 2012; Jarry et al., 2013; Osiurak et al., 2008b, 2009, 2010, 2011, 2013; Rothi et al., 1991, 1997; Wheaton & Hallett, 2007; see also Giovannetti et al., 2002, 2006) has been consistently documented in these patients (Baumard et al., 2016; Bozeat et al., 2002; Buchmann et al., 2020; Hodges, 2000; Jarry et al., 2020; Leiguarda et al., 2002; Lesourd et al., 2013, 2016). The use of familiar tools is a complex task that may rely on multiple cognitive processes, like semantic tool knowledge (Roy & Square, 1985; Stamenova et al., 2010, 2012), working memory (Bartolo et al., 2003; Cubelli et al., 2000), executive functioning (Goldenberg et al., 2007; Hartmann et al., 2005; see also Martyr & Clare, 2012), or body representations (Buxbaum, 2001; Goldenberg, 1995). A critical issue is, therefore, to understand which processes are at stake in the apraxia of tool use presented by patients with neurodegenerative diseases, as well as the role of physical understanding in this syndrome. A growing body of anthropological and neuropsychological literature has linked physical understanding to the ability to reason on the mechanical properties offered by tools and objects (Baillargeon, 1994; Baumard et al., 2016; Beck et al., 2011; Bozeat et al., 2002; Goldenberg, 2009; Goldenberg & Hagmann, 1998; Goldenberg & Spatt, 2009; Hodges, 2000; Lesourd et al., 2016; Ochipa et al., 1992; Osiurak, 2014; Osiurak et al., 2010, 2011, 2013). Physical understanding has been assessed in a variety of tasks (to be described below) hereafter referred to as mechanical problem-solving (MPS) tests. The latter is tool use tasks in which participants are asked to use novel tools and objects, meaning that the performance cannot rely on prior tool knowledge (e.g., making a hook with metal wire to extract a target out of a box) (Baumard et al., 2016; Beck et al., 2011; Heilman et al., 1997; Jarry et al., 2013; Lesourd et al., 2016; Ochipa et al., 1992; Osiurak et al., 2013). In view of positive correlations between performance in MPS tasks and familiar tool use tasks in patients with left-hemisphere damage, physical understanding appears necessary to perform even conventional actions and activities of daily living (Buchmann & Randerath, 2017; Goldenberg & Hagmann, 1998; Heilman et al., 1997; Jarry et al., 2013; Lesourd et al., 2019; Osiurak et al., 2013; Osiurak & Reynaud, 2020; Reynaud et al., 2016).

Since patients with neurodegenerative diseases may have apraxia of tool use, the question arises whether they also demonstrate impaired physical understanding, a topic that has received renewed interest in recent years. The goal of this review was, therefore, twofold. The first goal was to provide a full picture of the performance of patients with neurodegenerative diseases in tasks engaging physical understanding. To anticipate our findings, this has been mainly studied with mechanical problem-solving tests, thus the review will rapidly focus on these tests. The second goal was to study the links between familiar tool use and mechanical problem-solving skills, on the one hand, because both have been strongly linked in the literature, and on the other hand because in an ecological context, tool use is probably the most frequent situation in which humans have to reason on physical principles (e.g., solving intuitive physics paradigms without actually acting on the physical world is actually rare in everyday life). Importantly, dementia is far from being a monolithic category, thus different patients diagnosed with different neurodegenerative syndromes may have apraxia of tool use either because of physical understanding deficits per se or because of other cognitive impairments (e.g., semantic deficits). This in turn implies to discuss the mental processes that underlie human tool use. The findings will therefore be discussed in the light of the Four Constraints Theory of tool use or 4CT (Osiurak, 2014), the only integrative theory that acknowledges a critical role of physical understanding in tool use. To address these different issues, Sections 2.1 and 2.2 review the concepts and assessment methods of physical understanding; Section 2.3 describes the core assumptions of the Four Constraint theory as well as the neural bases of tool use and physical understanding; then Section 3 details and discusses the literature on physical understanding impairments in dementia, and their potential links to tool use.

2. The concept of physical understanding

2.1. The many names of physical understanding

2.1.1. Intuitive physics

The humankind has developed a very complex technological culture over time (Osiurak & Reynaud, 2020; Reynaud et al., 2016), to the point that the products of this culture have become a threat to the ecosystem itself. One may think that humans are, therefore, particularly efficient in their understanding of the physical laws. This is, however, not always the case, as demonstrated by studies on false beliefs that humans have about the laws that govern the physical world (e.g., causality, planetary movements; see also "implicit theories", Plaks, 2017). This fact has been captured by researchers with different terms like "intuitive physics", defined as "the knowledge underlying the human ability to understand the physical environment and interact with objects and substances that undergo dynamic state changes, making at least approximate predictions about how observed events will unfold" (Kubricht, 2017, p. 750). This concept has replaced the one of "naïve physics" that was used in early research studies (Caramazza et al., 1981; McCloskey, 1980, 1983b). The term "folk physics" has also been used in some studies, and refers to the spontaneous understanding one has of the physical world (Povinelli, 2000; Silva & Silva, 2006). An important aspect of intuitive physics is that the predictions that individuals make are not always consistent with the principles of Newtonian physics – hence the term "intuitive". The field of intuitive physics has investigated people's misconceptions when they try to apply physical laws to concrete situations. There has been a number of paradigms in the literature: Predicting the trajectory of a falling object dropped from a plane; predicting the trajectory of a ball when it comes out of a C-shaped tube; predicting the trajectory of a pendulum bob after the string is cut; drawing the water level in a tilted glass (for a review, see Kubricht, 2017). In these paradigms, a non-negligible percentage of adult participants (sometimes the majority of them) tends to make predictions that violate the laws of physics. As an example, in the C-shaped, or curved tube paradigm, half of the participants erroneously indicated that the ball would continue along a curved trajectory (McCloskey et al., 1980). In doing so, they demonstrated a "naïve impetus" theory, that is the belief, inherited from medieval theorists, that an object submitted to forces acquires an internal force itself (i.e., the impetus) in the direction of its motion (McCloskey, 1983a, 1983b). In fact, Newtonian physics rather predict a straight-line trajectory in the absence of external force. Similarly, the Galileo bias (Oberle et al., 2005) corresponds to naïve beliefs as to the effects of air resistance on objects. To sum up, individuals do not use the laws of physics when they solve such problems, but rather an approximation of these laws based on mental constructs. The latter are judgment heuristics that are implicit and not always accurate regarding the laws of physics, but that require less effort than explicitly understanding these laws while being accurate enough in everyday life situations requiring fast responses (Hubbard, 2019; Kozhevnikov & Hegarty, 2001).

2.1.2. Mechanical reasoning

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

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

2.1.3. Physical understanding in the neuropsychological literature

In the neuropsychological literature, physical understanding has been studied in patients with apraxia of tool use. In fact, the "apraxia of tool use" wording has been preferred to more classical categories like "ideational apraxia" or "conceptual apraxia" (i.e., the inability to use familiar tools due to semantic loss; De Renzi & Lucchelli, 1988; Ochipa et al., 1992; Rothi et al., 1991; Roy & Square, 1985), to refer to deficits in the use of both familiar and novel tools, and to suggest that the core deficit lies in the inability to reason about the physical properties of tools and objects (Osiurak, 2014; Osiurak, Aubin, Allain, Jarry, Etcharry-Bouyx, et al., 2008a; Osiurak et al., 2009, 2010, 2011, 2013). Neurological, especially stroke patients may indeed demonstrate impaired tool use (Baumard et al., 2014; Buchmann et al., 2020; Buchmann & Randerath, 2017; Goldenberg, 2009; Goldenberg & Hagmann, 1998; Goldenberg & Spatt, 2009; Jarry et al., 2013; Osiurak et al., 2009, 2013). In some studies, mechanical problem-solving skills have fallen into the broad scope of "non-verbal impairments" (Bozeat et al., 2000, 2002; Hodges et al., 1999, Hodges et al., 2000), while others have seen physical understanding as the expression of specific modes of reasoning. "Mechanical knowledge" has been defined as a specific subtype of knowledge of the mechanical function of tools and objects, allowing to understand the mechanical nature of problems; to understand the advantages that tools may afford, and hence to select tools; to develop new strategies while solving mechanical puzzles; and to make tools (Heilman et al., 1997; Ochipa et al., 1992; see also "practical knowledge", Roy & Square, 1985). More recently, it has been defined as non-declarative knowledge about the physical principles underlying tool use, acquired through experience (Osiurak & Reynaud, 2020). "Structural inference" has been defined as the ability to infer the proper function of novel tools based on the visual analysis of their structure, independently of prior knowledge (Goldenberg & Hagmann, 1998). The same authors (Goldenberg, 2009; Goldenberg & Spatt, 2009) have later made a link between motor functions and reasoning by assuming that during tool use actions, the "categorical apprehension" of mechanical relationships between tools and objects, or between different parts of multi-part objects, is a necessary condition to generate an optimal "chain" linking the body (e.g., the arm and hand posture) to the output of the action (e.g., the recipient of tool use). For example, it is the alignment of the screwdriver and the screw that constraints how to hold the screwdriver, and not the contrary. "Technical reasoning" is close to this proposal, and has been defined as the ability to determine possible mechanical relationships between tools and objects, as a function of properties of each (Osiurak, 2014; Osiurak et al., 2010, 2011). The common point between structural inference, categorical apprehension and technical reasoning, is to consider that mechanical problem-solving tasks call for dynamic, bottom-up reasoning, rather than retrieval of knowledge from memory. The technical reasoning hypothesis, in particular, assumes that tools have no intrinsic, decontextualized properties, and that the possible mechanical actions one can perform with tools are inferred from context-dependent relations between a tool and an object (i.e., one and the same tool may allow many different tool-object interactions). For the sake of clarity, and seeing the similarities between the abovementioned cognitive processes, we will hereafter refer to "physical understanding" only to refer to the ability to reason on the mechanical properties of tools and objects.

2.1.4. Physical understanding is implicit and pragmatic

Before going further, it is necessary to fully understand the nature of physical understanding. Why are humans sometimes bad at solving simple physics problems? This can be explained by the fact that physical understanding is partly based on prior knowledge that individuals have about the physical world ("technical expertise"; Osiurak & Reynaud, 2020). Developmental and comparative studies embracing the innate/acquired debate have suggested that human infants have a core ability to understand basic interactions between objects, or physics intuitions (e.g., objects move as connected wholes; they do not interact at a distance), that are later enriched through domain-specific experience of the physical world (see the "core knowledge theory" of Spelke & Kinzler, 2007; see also Baillargeon, 1994; Baillargeon et al., 1990, 1992; Needham & Baillargeon, 1993; Remigereau et al., 2016). This likely reflects the existence of an internal model acquired through both ontogenesis (e.g., the continuous experience of gravity and its consequences rapidly allows infants to make predictions on the behaviour of moving objects) and phylogenesis (e.g., all living species on Earth are exposed to gravity, hence the development and selection of mental representations fitting to it). This amounts to considering that physical understanding is pragmatic in nature: It intervenes and develops as individuals face new physical events and principles.

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

If physical understanding is implicit, pragmatic and supposedly efficient, then why are healthy adults bad at solving physics problems? Actually, this is the case only under certain circumstances. Indeed, the way problems are presented influences the performance, and correlational studies have reported only moderate associations between the performance obtained by healthy adults in different intuitive physics paradigms (Riener et al., 2005). The context-dependent nature of physical understanding, along with subject-dependent experience, may explain why individuals may have what appears like false or "magical" beliefs when trying to predict physical events, and why the performance of healthy adults is not consistent across seemingly identical intuitive physics paradigms. For instance, participants make erroneous predictions in the classical curved tube problem (i.e., predicting the trajectory of an object upon exiting from the tube), whereas they improve when asked to discriminate normal or abnormal trajectories based on dynamic animations (Kaiser et al., 1992) – a situation that is closer to naturalistic interactions with the physical world. Replacing the ball with water in this paradigm (hence likening the tube to a hose) improves the performance (Kaiser et al., 1986). Oberle et al. (2005) have found that the Galileo bias (i.e., the tendency to erroneously ignore air resistance during problem solving) is actually stronger in physics students, probably because they are generally asked to ignore air resistance when they solve physics problems.

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

2.2. How to assess physical understanding

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

Physical understanding, that said, has been more extensively investigated in apraxia studies. Four types of tests have been employed. In the unusual use of object and alternative tool selection tests (Figure 1A), participants are asked to select and/or use familiar tools in an unconventional manner (e.g., Derouesné et al., 2000; Osiurak et al., 2009). It means that tool use cannot rely on explicit semantic tool knowledge, and instead has to rely on the analysis of potential tool-object mechanical interactions. The limitation of these tests is that patients presumably have to inhibit the canonical function of the tool to be able to innovate. This is a problem with regard to functional fixedness (i.e., a cognitive bias that limits tool-related creativity with familiar tools; Duncker, 1945), hence the creation of mechanical problem-solving tests inspired by animal studies (e.g., Povinelli, 2000). In these tests, individuals are motivated to extract a target object out of a box by recourse to different novel tools and mechanical actions (e.g., push, pull, lever, hook). There have been some variations of this test, which common ground is that the solution has to be generated from scratch, rather than based on semantic tool knowledge. As a result, these tests control for semantic tool knowledge, and the performance relies purely on physical understanding. Contrary to classical problems used to assess executive functions (e.g., the Tower of London test, Shallice, 1982), the number of steps toward the solution is limited, meaning that these problems tend to control for working memory and planning skills as well. As a matter of fact, mechanical problems and multi-step problems are sensitive to parietal lobe lesions and dysexecutive syndrome, respectively (Goldenberg et al., 2007; Hartmann et al., 2005). In the novel tool test (Buchmann & Randerath, 2017; Goldenberg & Hagmann, 1998; Hodges et al., 1999; Figure 1B), participants are asked to select and use one of three novel tools, with the goal of lifting a wooden cylinder out of a socket. Nine cylinders are presented, and two distinct scores are collected for tool selection (independently of tool use) and tool application (independently of tool selection). Mechanical puzzles (Figure 1C) have rather put the emphasis on tool making as well as on the variety of mechanical actions needed to complete the eight items (Ochipa et al., 1992). In the eponym mechanical problem-solving test (Figure 1D), participants are asked to extract a target out of a box by selecting, combining and using up to eight novel tools that vary on length, diameter, material, bendability and colour. It is similar to the two latter tests, with four main differences. First, problem-solving cannot be based on mere spatial cognition, contrary to both spatial problems used in mechanical reasoning studies (Hegarty, 2004), and the novel tool test, in which comparing the shape of the tools and the shape of the cylinder may be sufficient to solve the problem. In contrast, the tools presented in the MPS test are visually very similar, thus forcing participants to reason on physical properties like bendability or rigidity. Second, contrary to the mechanical puzzles, the target cannot be reached using the fingers. Not only does it force participants to use tools, but it also makes the test usable with aphasic patients who could misunderstand the instruction of using a tool. Third, there are multiple solutions, meaning that participants have to make “the best choice” among several possible mechanical principles. As a result, it presumably puts higher loads on decision-making grounded in physical understanding. Fourth, it has been designed to assess MPS under two conditions: with choice, or without choice. In

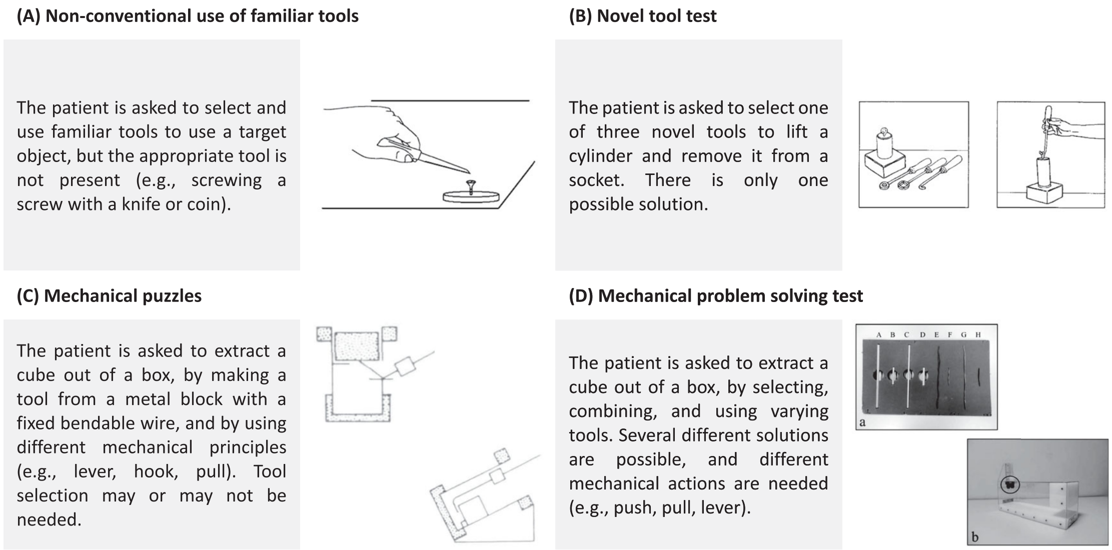

Figure 1. Examples of tests of physical understanding. The common point between these tests is that success requires to reason about the physical attributes of tools and objects. Pictures are from (A) Osiurak et al. (2009); (B) Goldenberg and Hagmann (1998); (C) Ochipa et al. (1992); (D) Lesourd et al.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

the choice condition, the participants are given all the eight tools to solve the problem, so that the number of potential mechanical interactions is high. In the no-choice condition, the examiner gives the participant only one, useful tool. This condition puts lower loads on visual exploration and tool selection, but the patient still has to understand which tool-box interactions are either relevant or irrelevant to the goal of extracting the cube.

2.3. The neurocognitive bases of tool use

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

2.3.1. The Four Constraints Theory of tool use

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

Since physical understanding is implicit and pragmatic, it cannot be reduced to a kind of explicit, semantic knowledge. Mccloskey et al. (1980, 1983a, 1983b) initially demonstrated that students with formal physics instruction may still use heuristics to formulate (incorrect) predictions regarding moving objects. The neuropsychological literature has provided strong arguments for a dissociation between semantic tool knowledge (i.e., knowledge about the conventional function and context of the use of tools and objects) and physical understanding. For instance, patients with left hemisphere stroke and apraxia of tool use may commit "severe" errors (e.g., eating soup with a fork; trying to press toothpaste out of a closed tube) that cannot be explained by missing tool knowledge (Goldenberg & Hagmann, 1998). There is now substantial evidence for a dissociation between familiar or novel tool use on the one hand, and semantic tool knowledge on the other hand (Bartolo et al., 2007; Baumard et al., 2016; Bozeat et al., 2002; Buxbaum et al., 1997; Buxbaum & Saffran, 2002; Goldenberg & Spatt, 2009;

Hodges et al., 1999, 2000; Negri, Lunardelli, et al., 2007; Osiurak & Badets, 2016; Silveri & Ciccarelli, 2009). On this ground, the 4CT assumes that tool use depends not only on semantic tool knowledge, but also on physical understanding. Both cognitive domains may nonetheless interact during familiar tool use (Osiurak, 2014). Imagine, for example, that you want to cut a piece of bread. Based on physical understanding alone, a knife, a saw, or even a chopper, share similar properties that are all useful to perform a "cutting" action. Semantic tool knowledge narrows the possibilities, and allows to select the kitchen knife, even though other tools may offer similar technical properties. The ability to mentally navigate through and within semantic categories to make canonical choices of tools is called "semantic reasoning" in the 4CT.

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

Importantly, these four cognitive components are not parallel routes to action execution. They are better viewed as cognitive layers that may be more or less necessary depending on the task. For example, novel tool use calls for physical understanding but not for semantic reasoning, while familiar tool use calls for both. It means that a physical understanding deficit should always be associated with both familiar and novel tool use impairments. This fractionation of the tool use system also allows predictions regarding different neurodegenerative diseases. For example, patients showing isolated semantic deficits should be able to use novel, but not familiar tools, while patients with physical understanding deficits should have difficulties using both.

2.3.2. The neural bases of physical understanding

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

A significant body of evidence has established the existence of a left-lateralized network for tool use. Liepmann (1905, 1920; see also Goldenberg, 2003) first demonstrated that apraxia was caused by lesions of the left hemisphere. Importantly, patients may exhibit severe difficulties when using not only familiar but also novel tools (Bartolo et al., 2007; Goldenberg et al., 2007; Goldenberg & Hagmann, 1998; Hartmann et al., 2005; Heilman et al., 1997; Jarry et al., 2013; Osiurak et al., 2009). Patients with left hemisphere stroke have more difficulties in the unusual use of objects test (Osiurak et al., 2009), in the novel tool test (Bartolo et al., 2007; Buchmann et al., 2020; Buchmann & Randerath, 2017; Goldenberg, 2009; Goldenberg et al., 2007; Goldenberg & Hagmann, 1998; Goldenberg & Spatt, 2009; Hartmann et al., 2005), in mechanical puzzles (Heilman et al., 1997), and in the mechanical problem-solving test (Jarry et al., 2013; Lesourd et al., 2016; Osiurak et al., 2013; for a review, see Baumard et al., 2014), in comparison with healthy controls and patients with right hemisphere stroke. Recent meta-analyses have strongly suggested that the left area PF (a subregion of the supramarginal gyrus) is critical to physical understanding, in both action execution and action observation paradigms (Figure 2; Osiurak &

Reynaud, 2020; Reynaud et al., 2016, 2019; see also Osiurak et al., 2020). Impairment in tasks assessing semantic tool knowledge, in contrast, has been associated with temporal lobe lesions (Binkofski & Buxbaum, 2013; Buxbaum, 2001, 2017; Buxbaum & Kalénine, 2010; Goldenberg & Spatt, 2009), while mental simulation probably depends on superior parietal brain regions (see Osiurak, 2014; Osiurak & Badets, 2016).

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

3. Physical understanding in neurodegenerative diseases

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

3.1. Methodological considerations

3.1.1. Research and selection of studies

To prepare this review, we performed a Title/Abstract Pubmed search on January 2021, using the following keywords: intuitive/folk/naïve physics, causal reasoning/thinking, magical thinking, impetus, momentum, gravity/gravitation, Piagetian, mechanical knowledge/reasoning/intelligence, technical reasoning, mechanical problem-solving, and dementia, ageing, Alzheimer's disease. Pubmed returned 196 results, including many duplicates. We also added some studies from our reference management software. Overall, 13 English-language studies were relevant to the topic of the review. Three of these studies used Piagetian paradigms (Emery & Breslau, 1987; Matteson et al., 1996; Thornbury, 1992), while the remaining 10 studies (Table 1) focused on mechanical problem-solving tests (Figure 1) in Alzheimer's disease (AD), semantic dementia (SD) and corticobasal syndrome (CBS).

3.1.2. Data extraction

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

3.1.3. Methodological considerations

We found substantial methodological discrepancy in the literature. The most obvious one is the use of different mechanical problem-solving tests to assess very similar psychological constructs (Figure 1). Furthermore, physical understanding may be assessed with or without a choice of tools (e.g., Lesourd et al., 2016; Ochipa et al., 1992). Tool selection and tool manipulation have been coded separately in some studies (Bozeat et al., 2002; Hodges et al., 2000; Spatt et al., 2002) while in other studies, scores

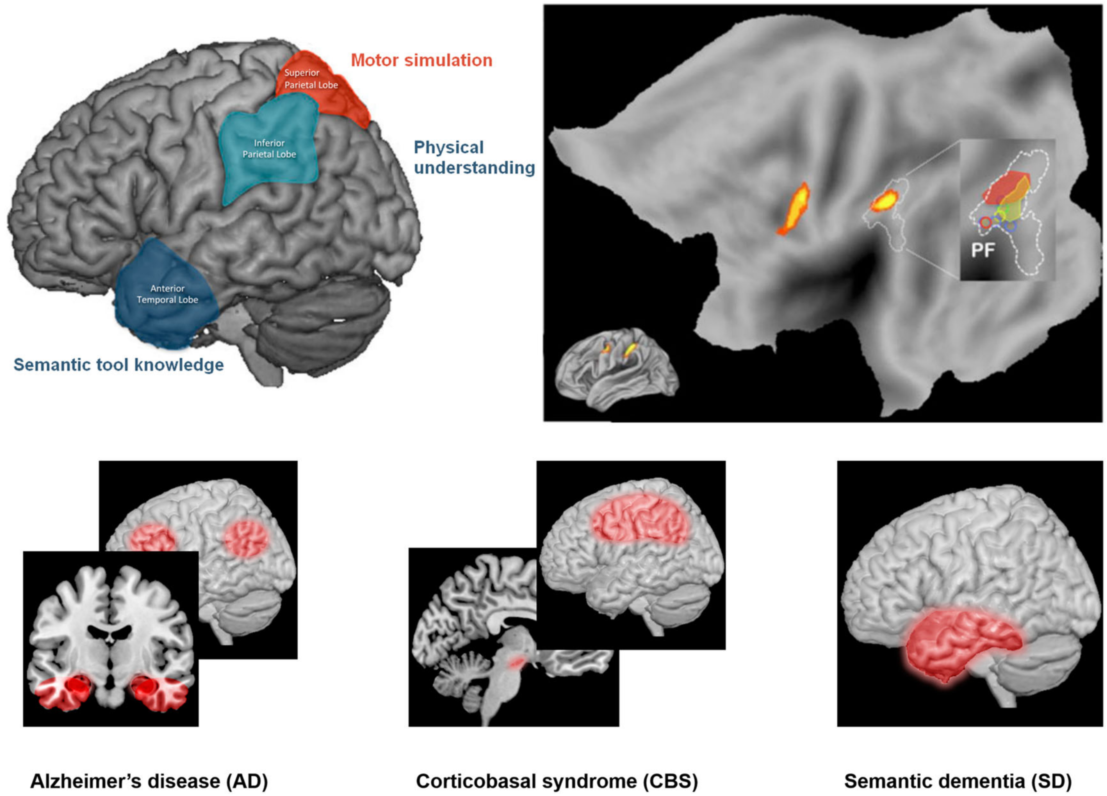

Figure 2. The neural bases of physical understanding and tool use. Upper panel, left: according to the 4CT of tool use, physical understanding and motor simulation are key components of familiar and novel tool use. Semantic tool knowledge is needed to use familiar tools in a conventional manner. Upper 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.

captured both selection and manipulation (Baumard et al., 2016, 2018; Buchmann et al., 2020; Lesourd et al., 2016). For example, mechanical puzzles have been assessed without choice (Ochipa et al., 1992) but also with choice, by coding tool selection and tool application separately (Bozeat et al., 2002). For the sake of clarity, we grouped both choice conditions and selection scores into a broad "choice condition" category, but no-choice conditions and manipulation scores into a broad "no-choice category". The number of foils also varied across studies: in the Novel Tool Test, patients have to select one of three novel tools (e.g., Bozeat et al., 2002; Hodges et al., 2000; Spatt et al., 2002). In the non-conventional use of familiar tools test, an array of five tools is presented (Derouesné et al., 2000; Ochipa et al., 1992). In the mechanical puzzles test, one to four tools have been presented in different studies (Bozeat et al., 2002; Ochipa et al., 1992). In the MPS test, eight tools are given to the patient (Baumard et al., 2016, 2018; Lesourd et al., 2016).

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

Finally, Table 2 shows that different tests of physical understanding may yield different results even in one and the same clinical population (e.g., the Novel Tool Test in AD). It is, for the time being, not possible to explain these variations because of variations of inclusion criteria as well. Diagnostic criteria keep evolving over time, thus different studies have included patients based on slightly different

Table 1. Studies of physical understanding and dementia.

Study	Population	N	Mean age	MMSE	Control group	Physical understanding: Task	Physical understanding: Conditions	Familiar tool use: Task	Familiar tool use: Conditions
Thornbury et al. (1992)	AD	30	71	NA	Yes	Piagetian scales	–	–	–
Matteson et al. (1996)	Dementia[a]	57	77	12.7 (11.4)	No	Piagetian scales	–	–	–
Emery and 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
						Mechanical puzzles	No choice	–	–
Derouesné et al. (2002)	AD	22	70	20 (3.9; 12–25)	Yes	Alternative tool selection	Choice	Real tool use	Choice and 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 and 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 and No choice	Single tool use	Considered a Choice condition
						Mechanical puzzles	Choice and No choice		
Spatt et al. (2002)	CBS	5	68	15 (7; 7–26)	Yes	Novel tool test	Choice and 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 and No choice	Real tool use	Choice and 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)

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

diagnostic criteria, meaning that patients from the same clinical population may actually correspond to different clinical phenotypes. For example, Spatt et al. (2002) included CBS patients with diffuse cognitive impairments (MMSE = 15/30) while Baumard et al. (2016) selected CBS patients with relatively isolated motor impairments (MMSE 24/30).

3.1.4. Data analysis

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

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

	Sample size				Familiar tool use				Non-conventional use of familiar tools				Novel tool test				Mechanical puzzles				Mechanical problem-solving test			
Study	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	–	–	–	–	–	–	92.2	60.1	–	–	–	–	–	–
Derouesné et al. (2000)	10	22	–	–	98	61	–	–	99	62	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	–	–	–	–	97	78	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Hodges et al. (1999)[a]	–	–	2	1	–	–	42	59.5	–	–	–	–	–	–	**100**	58	–	–	–	–	–	–	–	–
Hodges et al. (2000)[a,b]	8	–	9	–	91.9[f]	–	54.1[f]	–	–	–	–	–	97.6	–	**91.7**	–	–	–	–	–	–	–	–	–
	–	–	–	–	–	–	–	–	–	–	–	–	99	–	**89.3**	–	–	–	–	–	–	–	–	–
Bozeat et al. (2002)[b]	10	–	8	–	–	–	62.9[f]	–	–	–	–	–	97.7	–	**85.6**	–	77.7	–	**66.7**	–	–	–	–	–
	–	–	–	–	–	–	72.7	–	–	–	–	–	99.5	–	**94.6**	–	97.9	–	**92.7**	–	–	–	–	–
Spatt et al. (2002)	5	–	–	5	90–100	–	–	58	–	–	–	–	92–100	–	–	63.3	–	–	–	–	–	–	–	–
	–	–	–	–	–	–	–	–	–	–	–	–	92–100	–	–	46.7	–	–	–	–	–	–	–	–
Lesourd et al. (2016)[c]	31	31	15	–	63.5	38.5	48.3	–	–	–	–	–	–	–	–	–	–	–	–	–	54.7	30.7	**46.0**	–
	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	56.3	34	**56**	–
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
	–	–	–	–	63.5	38.5	46.8	31.1	–	–	–	–	–	–	–	–	–	–	–	–	56.3	34	**52.5**	34.8
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**

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 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 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 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 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 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 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] 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 in Figure 3.

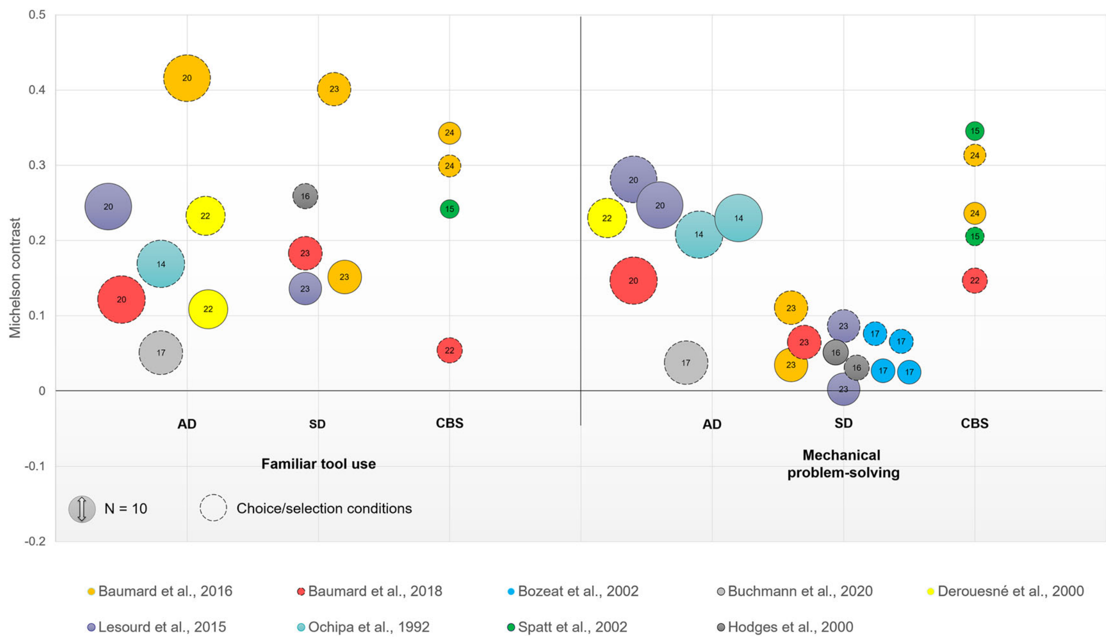

Figure 3. Control-patient difference in familiar tool use and mechanical problem-solving tests. The Y-axis displays Michelson contrast (range −1 to 1); the higher the value, the higher the control patient difference. The diameter of circles shows the sample size. Dotted lines correspond to either choice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

to give an overview of patients' physical understanding impairments – in counterpart, in Figure 3 these studies are illustrative at most.

We displayed the findings in two different ways so as to give a full picture of the data. First, in order to create Figure 3, we calculated Michelson contrasts as follows: (Control mean − Patient mean)/(Control mean + Patient mean). With this method, the difference score ranges from −1 to +1 and is scaled with respect to the sum of mean scores across groups; the higher the value, the higher the control-patient difference. Second, Figure 4 displays raw control-patient differences, and Table 2 displays control-patient differences weighted by sample size in order to avoid over-representing small samples. We used this second method so as to make our findings comparable to previous ones in Figure 4 (Osiurak & Reynaud, 2020).

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

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

3.2.1. Alzheimer's disease

Alzheimer's disease (McKhann et al., 2011) is characterized by a progressive cortical atrophy of the medial, basal and lateral temporal lobe, as well as of the parietal lobe. Frontal variants have also been described (Lam et al., 2013). The clinical presentation includes progressive, insidious worsening of cognitive functions that interferes with usual activities of daily living. The most prominent clinical impairments may regard not only episodic memory (i.e., the amnestic form of AD), but also language, semantic memory, visuospatial skills, or executive dysfunction. Apraxia has also been consistently reported (for a review see Lesourd et al., 2013). The evolution of the disease over years always converges toward a general cognitive deterioration, meaning that clinical dissociations are obvious only in the first years of evolution. Given this clinical heterogeneity, the label "Alzheimer's disease" may correspond to very different cognitive profiles, an issue that is even more complex considering the evolution of diagnostic criteria over time. The common point between all profiles, that said, is the progressive decline of the ability to interact with everyday tools and objects, as documented

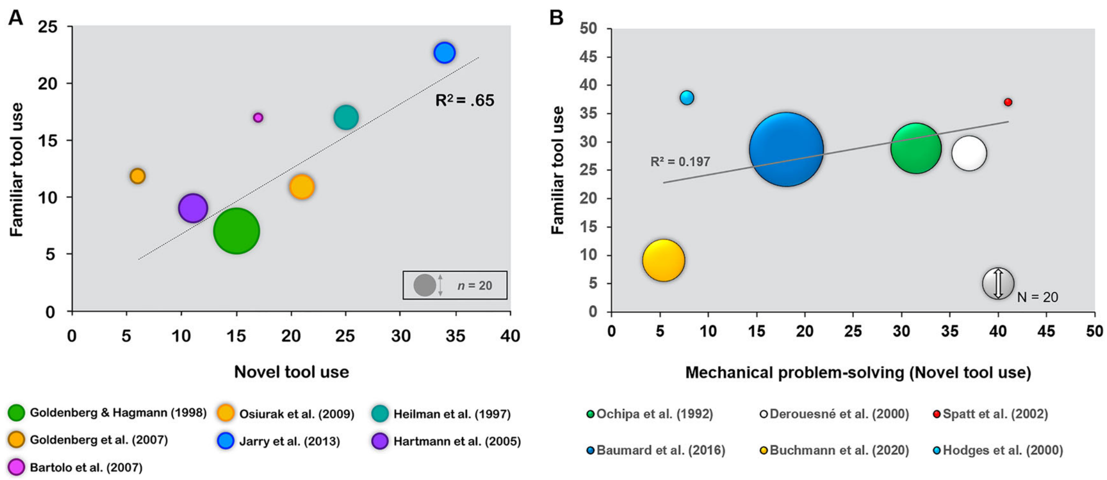

Figure 4. Associations between familiar tool use and mechanical problem-solving skills. Each circle is a study, and the diameter of circles corresponds to sample sizes. Values correspond to control-patient differences. Left panel: performance of patients with left hemispheric stroke, as displayed by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

by clinical inventories (e.g., instrumental activities of daily living; Lawton & Brody, 1969).

To our knowledge, the first studies on physical understanding in AD used Piagetian paradigms. Thornbury (1992) has found that healthy adults obtained scores corresponding to the concrete operational development stage (the highest stage in this study), whereas 50% of AD patients obtained scores corresponding to less mature developmental stages (sensorimotor stage characterized by a performance based on mental habits, imitation, and rudimentary trial and error strategies, 17%; preoperational stage characterized by egocentric thought and lack of abstraction, 33%). About a third of the patients failed mass, liquid, or surface conservation tests. Matteson et al. (1996) found similar results, albeit with lower methodological control (i.e., sample mixing Alzheimer and stroke patients; no control group). Using a taxonomy that is now outdated, Emery and Breslau (1987) compared "senile" (age-related) AD, and early-onset AD on conservation tests, both groups including patients with mild to severe dementia. They found impaired and similar performance in both groups (respectively, 19.2% and 15.8% of the maximum score, against 58.0% for healthy controls).

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

3.2.2. Semantic dementia

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

There is remarkable consistency in the literature showing that SD patients have normal performance in tests of physical understanding, with control-patient differences ranging from 7% with the Mechanical Problem-Solving test, to 8% with the Mechanical Puzzles and Novel Tool Tests (Table 2, Figure 3). As in AD patients, there is no clear effect of choice (control-patient difference: choice condition 8–12%; no-choice condition 0–10%). Of note, there is only little overlap between the performance of AD and SD patients (AD: 5-33%; SD: 7–8%), confirming that the performance of AD patients is disease-specific and not explainable by the mere presence of brain lesions – an assumption confirmed by the comparison of dementia with traumatic brain injury or multiple sclerosis (Buchmann et al., 2020). Using the Novel Tool Test, Hodges et al. (1999) were the first to demonstrate, in two cases, that patients may still solve mechanical problems in the context of severe semantic loss. They replicated this observation in a larger sample and found that the patients performed at ceiling, with flawless performance (Hodges et al., 2000). Bozeat et al. (2002) additionally demonstrated that their performance was normal with mechanical puzzles as the ones used by Ochipa et al. (1992). This has suggested that their normal performance was not problem-dependent, but rather due to the preservation of physical understanding. Interestingly, Hodges et al. (1999) had described the reverse profile in a patient with corticobasal syndrome, what Baumard et al. (2016) later confirmed in a group study. In the latter, only 12% of SD cases showed a deficit. To sum up, the now well-accepted dissociation in SD between physical understanding on the one hand, and semantic tool knowledge on the other hand, is in line with the core assumptions of the 4CT (Osiurak, 2014), as well as with Mccloskey et al.'s (1983) first finding that explicit knowledge is not a sufficient condition to interact with the physical world.

3.2.3. Corticobasal syndrome

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

Only four studies have investigated mechanical problem-solving skills in this population, yielding a control-patient difference of 23–41%. Spatt et al. (2002) used the Novel Tool Test, and found that all five cases had an impaired performance. The patients failed not only to manipulate the tools, but also to select them, leading Spatt et al. to conclude that motor dysfunction could not explain this finding. Baumard et al. (2016) found that CBS patients performed lower than controls in the MPS test. About 70% of cases failed at least one of the two conditions (i.e., choice, no-choice). Nevertheless, the frequency of physical understanding deficits in this population does not make consensus (22–100% of cases depending on studies). Contrary to what was found in other clinical groups, no-choice conditions may be slightly more difficult than choice conditions (control-patient difference: choice condition 23–32%; no-choice condition 21–49%). This depends on the coding systems used. Baumard et al. (2016) used a coding system capturing both selection and manipulation in the choice condition, but only manipulation in the no-choice condition; they found that the choice condition (C–P difference: 26.1%) was as difficult as the no-choice condition (C–P difference: 21.5%). By coding separately tool selection and tool manipulation in one and the same choice condition, Spatt et al. (2002) found that tool manipulation (C–P difference: 49.3%) was actually more difficult for these patients than tool selection (C–P difference: 32.7%). So, the core deficit in CBS patients is probably not a tool selection deficit, but rather a tool manipulation deficit. This questions the actual existence of a deficit of physical understanding in this population, because the latter should be associated with tool selection deficits – an issue to be discussed in further sections.

3.3. Does physical understanding predict familiar tool use skills?

Studies on stroke patients have demonstrated a strong relation between tests of physical understanding, and familiar tool use (Baumard et al., 2014; Osiurak & Reynaud, 2020). From Table 2 and Figure 3, it is clear that each of the three groups of interest demonstrate impaired use of familiar tools. The latter, however, may depend on multiple cognitive processes, and not only on physical understanding. So, this section discusses whether physical understanding may accurately predict familiar tool use. Figure 4 displays the association between control-patient difference scores for familiar tool use and for mechanical problem-solving tests, all patient groups, tasks and conditions combined, using the same method as in stroke studies (Osiurak & Reynaud, 2020). Figure 4 has two panels. The left panel corresponds to stroke studies only, and the figure has been extracted from Osiurak and Reynaud's (2020) study. The right panel is the analysis we performed in the present study, and it corresponds to patients with neurodegenerative diseases. Control-patient differences could be calculated for familiar tool use in eight studies (see Table 2; Baumard et al., 2016; Baumard et al., 2018; Buchmann et al., 2020; Derouesné et al., 2000; Hodges et al., 2000; Lesourd et al., 2016; Ochipa et al., 1992; Spatt et al., 2002). We removed two studies (Baumard et al., 2018; Lesourd et al., 2016) to avoid sample overlap. The analysis in Figure 4 (right panel) is therefore based on six studies. While the comparison is illustrative at most with such a limited dataset, the correlation seems weaker in patients with neurodegenerative diseases than in patients with stroke (Osiurak & Reynaud, 2020), especially if one considers the weight of Buchmann et al.'s (2020) study (see peculiarities of this study above and in the captions of figures and tables). This is probably because of the specific nature of brain lesions and cognitive dysfunction in neurodegenerative diseases – a less homogeneous clinical group than left-hemisphere stroke patient groups.

Patients with AD show relatively similar levels of performance in tests of physical understanding and familiar tool use, with the only limited effect of choice (familiar tool use: choice condition 9–37%; no-choice condition 19–25%). Derouesné et al. (2000) found that the performance on different tool use tests, including the alternative tool selection test, was a good predictor of the performance in activities of daily living. In the studies by Baumard et al. (2016, 2018), 44–65% of AD patients failed mechanical problem-solving tests, and 71–89% of these cases failed to use familiar tools properly. Taken together, physical understanding and semantic tool knowledge were good predictors of the overall familiar tool use performance. We performed the same regression as the one displayed in Figure 4, based on Alzheimer's studies only (Baumard et al., 2016; Buchmann et al., 2020; Derouesné et al., 2000; Ochipa et al., 1992). We found a positive association between both tests ($R^2 = .75$; or $R^2 = .81$ considering choice conditions only). On this ground, one could assume that the performance on tests assessing physical understanding predicts well the performance on familiar tool use tests. It should be acknowledged, however, that one study (Buchmann et al., 2020) highly influenced the correlation (see Supplementary Figure 1), so future studies are needed to confirm this association.

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

Interestingly, patients with CBS show different, if not reverse patterns of performance. As was the case for tests of physical understanding, the no-choice condition of familiar tool use may be more difficult than the choice condition (control-patient difference: choice condition 10–37%; no-choice condition 32%; see also Figure 3), a dissociation found only in the CBS group. This suggests that semantic tool knowledge is not a relevant predictor of familiar tool use in this group. Physical understanding is impaired in up to 100% of CBS cases depending on coding systems, and 50–100% of these cases show impaired familiar tool use (Baumard et al., 2016, 2018; Spatt et al., 2002). On this ground, the performance on tests of physical understanding may seem a good predictor of familiar tool use skills. This assumption, however, calls for further confirmation because only two small cohorts have been described, with substantial methodological discrepancy.

3.4. Is physical understanding really impaired in neurodegenerative diseases?

The fact that the performance in tests of physical understanding predicts the performance in familiar tool use tests, does not mean that physical understanding itself is the (only) predictor. Presumably, mechanical problem-solving tests engage not only physical understanding, but also motor functions for the actual manipulation of tools, episodic memory to retain the instructions, and executive functions to deal with the problem's novelty. Even though stroke studies have clearly demonstrated the autonomy of physical understanding toward motor and executive functions (Goldenberg & Hagmann, 1998; Goldenberg et al., 2007; Hartmann et al., 2005; Liepmann, 1905, 1920), little is known as to how these functions may interact during mechanical problem-solving by patients with neurodegenerative diseases. Lesourd et al. (2016) found that working and episodic memory scores were good predictors of the performance on the mechanical problem-solving test. Baumard et al. (2018) explored the weight of these dimensions. They found (1) that 47% of AD patients (but 7% and 22% of SD and CBS patients) failed a modified version of the Tower of London test assessing planning skills (Jarry et al., 2013); (2) double dissociations between this test and mechanical problem-solving; (3) a positive correlation ($r = .47$) between both tests. About 94% of these AD patients failed to use familiar tools. In contrast, episodic memory played only a negligible role. In the only qualitative study of tests of physical understanding, Lesourd et al. (2016) have compared not only the performance, but also the strategy used by AD patients and patients with left-hemisphere stroke (LHS; Osiurak et al., 2013). They counted the time that patients spent performing tool-box interactions, a measure that was supposed to indicate the underlying understanding of physical tool-box potential interactions. While both AD and LHS patients failed the test, only LHS patients had abnormal strategies (i.e., less tool-box interactions). This is also consistent with the fact that LHS patients, but not early-stage AD patients, commit severe tool use errors revealing misconception about physical interactions. In summary, patients with AD do have problem-solving deficits, but based on the current state of the literature, it seems improbable that it may reflect actual deficits of physical understanding in all patients. As previously emphasized by Lesourd et al. (2016), apraxia of tool use may not be of the same nature in LHS and AD patients. Patients with acute left hemisphere stroke generally demonstrate "true" deficits of physical understanding, whereas patients with AD have unspecific, yet sometimes multiple cognitive deficits that may secondarily hamper the use of familiar and novel tools (at least in the first stages of the disease, as we will argue in the next section). It is also quite plausible that some patients fail to solve mechanical problems not because of physical understanding deficits but rather because of either early sensory/attentional processing deficits (preventing patients from extracting useful information about the physical world), or mental simulation deficits (preventing them from predicting how different materials may interact; Osiurak, 2014; Battaglia et al., 2013).

As regards the CBS group, Baumard et al. (2018) found a strong and positive association ($r = .98$) between performance in the MPS test, and performance in a test assessing fine motor dexterity. In fact, CBS patients had abnormal time-based composite scores (82% of patients showed a deficit), but better accuracy-based scores (22% of patients showed a deficit; Baumard et al., 2016, 2018). This, along with the higher performance in choice than in no-choice conditions, suggests that CBS patients had mainly motor production deficits, preventing them from manipulating novel tools, while true deficits of physical understanding were rare. On this ground, future works should probably assess physical understanding while controlling for tool manipulation, as did Lesourd et al. (2017) in stroke patients, and test the whole cognition.

3.5. What is the effect of global cognitive deterioration?

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

In comparison, more recent studies have included patients with higher MMSE scores. As shown in Figure 3, patient groups with MMSE scores ranging from 14 to 22 showed similar levels of impairment in tests of physical understanding. These studies have led us to conclude that AD patients have mechanical problem-solving deficits, but probably not "true" physical understanding deficits (see Section 3.4). They have also showed that the performance in tests of physical understanding was not well predicted by general cognitive deterioration (Derouesné et al., 2000). Therefore, there is probably a shift, with the evolution of the disease, in the comprehension that patients have of the physical world. We assume that physical understanding does decay over time (there is actually no reason why the left area PF should resist more than other brain regions to the progression of cortical atrophy), yet this deterioration probably occurs in late stages of the evolution, in patients with moderate to severe dementia. Such deficits probably induce more general cognitive deficits and hence significant loss of autonomy, in that physical understanding has been proposed to ground higher cognition (e.g., forming concepts and goals, talking about the world, detecting situations demanding special attention; Battaglia et al., 2013). In other words, functional autonomy probably goes through three phases: (1) Pre-clinical stage: normal tool-related cognitive mechanisms (i.e., physical understanding, executive functions, semantic tool knowledge, motor simulation); (2) Clinical stage: patients may have difficulties to use familiar tools under some circumstances because of associated cognitive deficits (e.g., executive dysfunction may hamper novel or multi-step activities; semantic memory loss may prevent patients from using tools in a conventional way), yet physical understanding is spared. As a result, patients may show good residual tool use skills, and hence functional autonomy remains relatively spared; (3) Functional dependence: physical understanding is altered, causing severe loss of autonomy and leading to institutionalization.

A similar rationale may apply to CBS patients. Spatt et al. (2002) included patients with widespread cognitive impairments (mean MMSE = 15; language, semantic and visual-spatial impairments), whereas Baumard et al. (2016, 2018) included patients with relatively isolated motor deficits (mean MMSE = 24 and 22, respectively). As a matter of fact, Spatt et al. reported more severe physical understanding impairments than Baumard et al. So, CBS patients with diffuse cognitive impairments (whether because of longer evolution, or due to particular patterns of atrophy and clinical presentations) have shown more severe impairments on physical understanding tests than CBS patients with isolated motor deficits. Future studies are needed to confirm the predictive value of physical understanding deficits for health care decisions.

4. Concluding remarks and future directions

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

Surprisingly, however, the literature on novel tool use remains sparse, and there has been no study using intuitive physics paradigms in patients with dementia. Since these patients show relatively specific cognitive impairments, documenting associations and dissociations between familiar tool use and different paradigms of physical understanding may be of great interest. This could help to improve neuropsychological evaluations, but also to implement new, disease-specific care strategies. Assuming that some human-tool interactions may not rely on physical understanding (e.g., reach and grasp movements, simple predictions regarding moving objects) may help better analyse some patients' residual tool use skills. After all, apes are capable of causal reasoning when tools are not involved (Vaesen, 2012). Whether impairments of physical understanding, in isolation or associated with other cognitive deficits, accurately predict particular error types in familiar tool use tasks, as well as the functional outcome, deserves further studies. Some questionnaires may be of use in this regard (e.g., Force Concept Inventory, Hestenes et al., 1992). It is also important for future studies to make available the performance of individual cases, and not only group-level values, because the latter may overlook between task dissociations in individual patients (Caramazza, 1986; Negri et al., 2007). This will allow studying potential dissociations between different tool use conditions and tests of physical understanding, and hence deriving inferences on possible fractionations of the physical engine.

This review has some limitations. First, there has been substantial overlap between some studies, thus the generalization of the findings has only limited scope. Second, diagnostic criteria have considerably evolved over years, meaning that studies conducted in the 90s are not fully comparable to studies conducted in the 2010s. Since taxonomies are likely to evolve in future years, studies should probably not merely depict the performance of clinical groups, but also provide a fine-grained analysis of cognitive profiles. This may also allow to control for cognitive dimensions other than physical understanding, but that may prevent patients from completing problem-solving tests (e.g., working memory, episodic memory, executive functioning, visual-spatial skills). Third, most of the studies included in this review could not escape a publication bias. Since studies with significant control-patient differences are more easily published than studies with negative findings, the effect of dementia on physical understanding might be over-estimated. For instance, when causal reasoning tasks (in which participants are asked to predict the movement of an object) are used as control tasks for comparison with social reasoning tasks, there is actually no difference between AD patients and healthy controls (e.g., Verdon et al., 2007). It is also possible that these tests are not fully equivalent to mechanical problem-solving tests. To overcome this bias, future studies are encouraged to compare different clinical populations, as well as different paradigms in the same population, with the intention to infer which dimensions are at the root of disease-specific clinical impairments. In a "problem complexity approach", Proffitt and Gilden (1989) have made a distinction between easy and difficult intuitive physics tasks, defined as a function of the number of physical dimensions of motion that participants have to deal with. This may be a relevant independent or control variable in future clinical studies, because it finds echo with theories of tool use considering that errors arise from the interaction between task complexity and limited cognitive resources (e.g., Giovannetti et al., 2002). Fourth, we have accepted different concepts as circumstantial synonyms, given both the resemblances between concepts, and the scarcity of the literature on physical understanding and dementia. Yet, perhaps they are not fully superimposable: In intuitive physics paradigms, the normal performance (frequent in the normal population) is to make an erroneous prediction, whereas in tool use paradigms, the normal performance is defined as a successful tool use action, which implies that the participant correctly used the laws of physics. To our knowledge, there has been no study addressing this issue and comparing different paradigms on a one-to-one basis under varying conditions (e.g., concreteness, effect of perceptual/contextual cues, number of physical dimensions; see Section 2.1.4).

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