# Identification of taxonomic and thematic relationships: Do the two semantic systems have the same status in semantic dementia?

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**Abstract**

Introduction: Disequilibrium between the taxonomic and thematic semantic systems was previously hypothesized in participants with semantic dementia (SD), without rigorously assessing their ability to identify the two types of semantic relationships. Therefore, the aim of the present study was to directly compare the ability of 10 participants with SD, 10 participants with Alzheimer's disease (AD), and 20 controls to identify thematic versus taxonomic relationships.

Methods: Participants performed an explicit forced-choice picture-matching task in which they had to determine which of two pictures of choice was semantically related to the target picture. Target pictures could display natural or artifact objects. Each target was presented once with a taxonomically related picture and once with a thematically related picture.

Results: Analyses of correct thematic and taxonomic matches as a function of target domain showed that the performance of the two groups of patients differed in the taxonomic conditions but not in the thematic conditions, demonstrating a relative preservation of thematic knowledge in SD. Additional correlation analyses further indicate that the particular status of thematic relationships in SD was even stronger for artifact concepts.

Conclusions: Results provide evidence of the heterogeneous nature of semantic knowledge disruption in SD, and could be regarded as being consistent with the existence of two neuroanatomically and functionally distinct semantic systems. Results further stress the relevance of performing a more detailed and complete assessment of semantic performance in participants with SD, in order to capture the impaired but also preserved aspects of their knowledge.

*Keywords:* semantic dementia; taxonomic system; thematic system; semantic disequilibrium; explicit matching task

## 1. Introduction

Semantic dementia (SD) is a rare neurodegenerative disease (Belliard, Merck, Jonin, & Vérin, 2013; Bozeat, Lambon Ralph, Patterson, Garrard, & Hodges, 2000; Landin-Romero, Tan, Hodges, & Kumfor, 2016; Neary et al., 1998; Snowden, Goulding, & Neary, 1989). If SD is also currently considered as the semantic variant of primary progressive aphasia (Gorno-Tempini et al., 2011; Mesulam, 2001; Mesulam, Grossman, Hillis, Kertesz, & Weintraub, 2003), the syndrome largely exceeds the language disorders (Botha & Josephs, 2019). Its hallmark is a selective loss of conceptual knowledge, responsible for deficits in naming, word meaning comprehension, and the identification of objects and persons in different input modalities (Bozeat, Lambon Ralph, Patterson, Garrard, & Hodges, 2000; Luzzi et al., 2007; Snowden, Thompson, & Neary, 2012; Snowden et al., 2017). In the early stages of the disease, the semantic memory alteration occurs without any impairment of general intellectual ability, visuoperceptual abilities or day-to-day memory (Adlam, Patterson, & Hodges, 2009; Irish et al., 2016). Language remains fluent and well-structured, without any phonological or grammatical errors, and only subtle abnormalities in the syntactic structure of speech have been reported (Meteyard & Patterson, 2009). Astonishingly, despite their massive semantic deficit, patients with SD remain relatively independent in some activities of daily living (Bier et al., 2013; Bier & Macoir, 2010). The syndrome arises out of temporal lobe atrophy, often bilateral but predominantly on the left side in many cases (Chan et al., 2001; Hodges, Patterson, Oxbury, & Funnell, 1992).

In SD, the semantic knowledge impairment is frequently described as general and pervasive. Patterson, Nestor, and Rogers (2007) defined the disorder as “a selective impairment to semantic abilities that affects all modalities of reception and expression, for all kinds of concepts, more or less equally, and it is the consequence of relatively focal brain lesions” (p. 978), as the conceptual representations are stored in a unitary *amodal* format in the right and left anterior temporal lobes (ATLs). Nonetheless, dissociations within this semantic disruption have often been reported between the verbal and nonverbal input modalities, within categories of knowledge, and between visual and functional features (see Gainotti, 2017, 2018, for recent reviews; Merck et al., 2013; Merck, Jonin, Laisney, Vichard, & Belliard, 2014; Merck et al., 2017; Snowden et al., 2012; Snowden et al., 2017). A reversal of the concreteness effect has also been shown in SD (Breedin, Saffran, & Coslett, 1994; Joubert et al., 2017; Macoir, 2009 ; Reilly, Cross, Troiani, & Grossman, 2007; Yi, Moore, & Grossman, 2007) with poorer comprehension of concrete words than abstract words. The authors explained this effect by the fact that the meaning of abstract words relies on verbal associations, whereas concrete words area highly imageable and depend upon perceptual features that are disturbed in SD.

In a previous study, Merck et al. (2014) investigated the nature of the semantic disorders of participants with SD by means of an implicit priming paradigm in which participants had to perform a lexical-decision task on target names preceded by object names sharing certain attributes with the target. The analysis focused on two different types of attributes: visuoperceptual (visual; e.g., *ostrich* priming *neck*) versus contextual-functional (contextual; e.g., *bed* priming *pillow*). Results demonstrated the robustness of contextual features compared with visual features in a group of eight participants with SD. For age-matched healthy controls, a significant priming effect was found in the visual but not contextual condition, whereas the SD group exhibited the opposite pattern of performance. At 1 year follow-up, data provided evidence of the reliability of the dissociation between priming effects in the two attribute conditions, as the number of participants exhibiting the dissociation between the two priming conditions increased between baseline and follow up. The authors interpreted the presence of a particular priming effect in participants with SD but not in controls as a sign of semantic disequilibrium between two semantic systems : the taxonomic and the thematic systems (Denney, 1975; Estes, Golonka, & Jones, 2011; Lin & Murphy, 2001; McRae, de Sa, &

Seidenberg, 1997; McRae, Cree, Seidenberg, & McNorgan, 2005; Medin and Ortony, 1989). The two systems refer to two different ways of organizing knowledge in semantic memory. On the one hand, the taxonomic system organizes knowledge based on similarity and gathers objects that share features, with an important weight of visuoperceptual features (Kalénine et al., 2009) (e.g., both ostriches and ducks have necks). On the other hand, the thematic system organizes knowledge based on complementarity in events and brings together objects belonging to the same spatial and/or temporal context (e.g., lawnmower and grass have complementary roles in the cutting grass event). Accordingly, the contrasting patterns of priming effects observed among participants with SD versus controls may have reflected the differential recruitment of one of two semantic systems (taxonomic vs. thematic). More specifically, Merck et al. (2014) argued that in controls, taxonomic processing was automatically favored over thematic processing. Controls thus automatically drew on the taxonomic system, leading to a significant priming effect for visual features, but no priming for contextual features. By contrast, in the participants with SD, the deterioration of visuoperceptual attributes impeded taxonomic processing and thus brought thematic system processing to the fore. These interpretations are supported by growing arguments in favor of the co-existence of two distinct but parallel taxonomic and thematic semantic systems in healthy adults (Landrigan & Mirman, 2018; see Mirman, Landrigan, & Britt, 2017, for a recent review; Xu, Qu, Shen, & Li, 2019) with a probable competition in the recruitment of the two systems (Maguire, Brier, & Ferree, 2010). Taken together, these arguments allowed Merck et al. (2014) to interpret their findings as mentioned above-that is, in terms of the differential recruitment of the competing taxonomic and thematic systems.

Dissociations between subtypes of semantic relationships that may overlap with the taxonomic/thematic distinction have already been reported, such as the distinction between "conceptual similarity" versus "associative links" (Hoffman, Jones, & Lambon Ralph, 2013;

Jackson, Hoffman, Pobric, & Lambon Ralph, 2015) or between “category coordinates” versus “functional properties” (Tyler & Moss, 1998). Nevertheless, “associative” or “functional” labels have been used to refer to heterogeneous relationships, encompassing both “used to perform an action” relationships (e.g., *desk – work*), contextual relationships (e.g., *crocodile - river*), as well as lexical associations (i.e., relations between two concepts in idiomatic expressions, proverbs and citations; e.g.: *needle – haystack* or *fox - sly*). Yet pure lexical associations have been shown to rely on nonsemantic processes (Rogers & Freedman, 2008; Yee, Overton, & Thompson-Schill, 2009). Such heterogeneity makes it difficult to draw inferences about the status of so-called “associative” or “functional” relationships. For these reasons, we use the terminology corresponding to the theoretical framework of the taxonomic and thematic systems as it offers more circumscribed and comparable principles for the organization of object concepts (Mirman et al., 2017).

Although the distinction between taxonomic and thematic knowledge is now well accepted, the cognitive and cerebral mechanisms underlying the organization of the two types of semantic knowledge remains a matter of debate. According to the “hub and spoke” influential model of semantic cognition (Lambon Ralph, Cipolotti, Manes, & Patterson, 2010; Patterson et al., 2007; Rogers et al., 2004), the anterior temporal lobe (ATL) is the core region of a single convergence zone (the “hub”) that brings together various modality-specific information from different sensory, motor and linguistic regions (the “spokes”) into an amodal and coherent stored representation. Thus, this model assumes subtle rather than substantial differences between taxonomic and thematic processing since both taxonomic and thematic knowledge would be represented within a single, unified semantic system that heavily relies on the ATL (Lambon Ralph, Jefferies, Patterson, & Rogers, 2017; Rice, Hoffman, & Lambon Ralph, 2015). In the Jackson et al. (2015)’s study, for instance, the authors showed only weak differences in the neural substrates involved in taxonomic and thematic processing, which were considered to reflect graded differences in task difficulty. Another theoretical view proposes instead to regard taxonomic and thematic knowledge as two distinct semantic systems based on evidence for partially but substantial distinct neural bases between the two processing (Kalénine et al., 2009; Schwartz et al., 2011; Xu et al., 2018). Taxonomic processing has been found to activate bilateral visual association areas (cuneus and lingual gyrus, Brodmann area 18; Kalénine et al., 2009), in addition to ATL regions (Lewis, Poeppel, & Murphy, 2015; Schwartz et al., 2011; Xu et al., 2018). By contrast, thematic relationships have been found to be associated with the posterior temporoparietal cortex, which is known to be involved in motion, action and spatial processing (de Zubicaray, Hansen, & McMahon, 2013; Kalénine & Buxbaum, 2016; Mirman & Graziano, 2012; Schwartz et al., 2011; Xu et al., 2018). In SD, neural damage follows a rostrocaudal gradient in the temporal lobes as the disease progresses, with the anterior parts being more severely affected than the posterior ones (Brambati et al., 2015; Bright, Moss, Stamatakis, & Tyler, 2008; Chan et al., 2001; Desgranges et al., 2007; La Joie et al., 2014; Leyton, Britton, Hodges, Halliday, & Kril, 2016). Therefore, according to the view of two distinct semantic systems, the important neuroanatomical and neurofunctional dissociations between taxonomic and thematic processing would lead to an earlier degradation of taxonomic knowledge compared to thematic knowledge in SD.

To compare the integrity of the two types of knowledge more directly and to test the hypothesis of relatively spared thematic processing in SD, we administered the forced-choice picture-matching task used by Kalénine et al. (2009, 2016) to 10 participants with SD. This explicit matching task assesses the identification of thematic and taxonomic relationships for the same target object (e.g., animal, fruit, tool or vehicle). In healthy adults (Kalénine et al., 2009), as well as in participants with stroke (Kalénine & Buxbaum, 2016), it had been demonstrated an interaction between type of semantic relationship and domain of knowledge, with an advantage for the identification of taxonomic over thematic relationships for natural entities, and the opposite pattern for artifacts. Again, this interaction pattern is consistent with the importance of perceptual attributes for taxonomic relationships and contextual/functional attributes for thematic relationships (Cree & McRae, 2003; McRae et al., 2005), as perceptual attributes tend to be more central for natural objects and contextual/functional ones more relevant for artifacts, according to the sensory/functional theoretical framework (SFT; Warrington & Shallice, 1984).

In the present study, we therefore asked whether participants with SD, as compared with healthy controls and non-SD participants, would show a different profile of semantic performance regarding the type of semantic relationship (taxonomic, thematic), and the domain of knowledge (natural, artifacts). Critically, in the SD group, we hypothesized an advantage for the identification of thematic relationships over taxonomic relationships, and that this advantage should be more pronounced for artifacts than for natural entities. We also examined whether this particular profile was modulated by disease severity. Importantly, we expected this profile to be specific of SD and therefore compared taxonomic and thematic performance of participants with SD with that of participants with Alzheimer's disease (AD). AD is also well characterized by a semantic breakdown (Adlam, Bozeat, Arnold, Watson, & Hodges, 2006; Giffard et al., 2001; Giffard et al., 2002) but to a lesser degree than SD (Laisney et al., 2011) and with partially intact semantic knowledge (Rogers & Freedman, 2008). The group of participants with AD was thus included as a stricter control group to ensure that the asymmetry between taxonomic and thematic performance that we expected to see in SD compared to healthy controls was specific to this pathological condition and could not be due to near-ceiling effects in healthy controls. Accordingly, we expected participants with SD to show impaired taxonomic knowledge but relatively preserved thematic knowledge, in particular when related to artifacts, in comparison to participants with AD.

## 2. Materials and methods

### 2.1 Participants

All participants gave their informed consent before being included in the study. The experiment was conducted in accordance with the Declaration of Helsinki (1964, 2013) and with the current French legislation (Huriet Act, 1988).

Their demographic and clinical features are set out in Table 1.

Table 1. General demographic and clinical features of participants.
* : significant difference between the patients with SD and the controls
§ : significant difference between the patients with AD and the controls
† : significant difference between the patients with SD and the patients with AD

| | **Healthy controls** | | **Participants with semantic dementia (SD)** | | **Participants with Alzheimer's disease (AD)** | |
|---|---|---|---|---|---|---|
| **Sex (male; female)** | 6;14 | | 6;4 | | 5;5 | |
| | **Mean (standard deviation)** | **Range** | **Mean (standard deviation)** | **Range** | **Mean (standard deviation)** | **Range** |
| **Age in years** | 67.9 (5.5)§ | 60-79 | 69.6 (5.4) | 64-80 | 74.5 (6.2) § | 64-82 |
| **Education in years** | 15.9 (2) §* | 12-18 | 11.2 (4.2) * | 7-20 | 8.4 (2.1) § | 7-12 |
| **MMSE (/30)** | 28.9 (1) §* | 27-30 | 23.5 (3)* | 18-28 | 23.7 (2.7) § | 19-29 |
| **Disease duration (months)** | | | 55.2 (35) | 12-120 | 63.6 (26.7) | 36-120 |
| **AD biomarker status (positive; negative)** | | | Negative: 7 | | Positive: 10 | |
| **Side of temporal atrophy (L = left; R = right)** | | | 6 L > R<br>4 R > L | | | |

#### 2.1.1 Participants with SD

Ten participants fulfilling the diagnostic criteria for SD (Neary et al., 1998) were included in our study. They also fulfilled diagnostic criteria for semantic variant of primary progressive aphasia (svAPP), Gorno-Tempini et al. (2011). Nonetheless, we preferred to retain the terminology of *semantic dementia* in this study. The terminology of svAPP remains criticized, as it focuses on the language symptoms and excludes other more behavioral presentations of this affection (Botha & Josephs, 2019).

The participants with SD were recruited at the memory clinic of Rennes University Hospital. Two of these 10 participants (SD4 and SD5) had been also included in Merck et al. (2014)'s previous study featuring a semantic priming paradigm. Almost all of them (9/10) were right-handed, and the remaining one was left-handed. They had no history of neurological or psychiatric disorders, or drug or alcohol abuse. Their physical neurological examination was unremarkable. They all presented with the typical clinical features of SD: a history of complaints about worsening comprehension deficits, anomia, and difficulty identifying objects and/or persons, reflecting a predominant and distressing loss of conceptual knowledge, contrasting with the relative preservation of day-to-day memory and perceptual abilities. Speech was still fluent, without any phonological or syntactic errors. All the participants with SD underwent a comprehensive neuropsychological battery, in addition to the forced-choice picture-matching task. This battery consisted of assessments of their *general cognitive functioning* (Raven's Coloured Progressive Matrices; Raven, Raven, & Court, 1998; Dementia Rating Scale, DRS; Mattis, 1976; Mini Mental State Examination, MMSE; Folstein, Folstein, & McHugh, 1975), *nonverbal episodic memory* (La Ruche visuospatial learning task; Violon, 1984; The Doors visual recognition task; Baddeley, Emslie, & Nimmo-Smith, 1994; Delayed recall condition of the Rey–Osterrieth Complex Figure Test–Form A; Osterrieth, 1944), and *working memory* (Digit Span Forward and Backward, Wechsler Adult Intelligence Scale-Revised, WAIS-R; Wechsler, 1981). *Language skills and semantic knowledge* were assessed by means of regular and irregular word reading, the single-word repetition subtest of the Boston Diagnostic Aphasia Examination (Goodglass & Kaplan, 1972), and the GRECO neuropsychological semantic battery (BECS-GRECO; Merck et al., 2011), which assesses the integrity of the same 40 items (20 biological entities and 20 manufactured entities) through a picture-naming task and verbal and visual semantic matching tasks. *Visuoperceptual performance* was also measured (copy condition of the Rey–Osterrieth Complex Figure Test–

Form A; Embedded Figures subtest of the Protocole d'Evaluation des Gnosies Visuelles, PEGV; Agniel, Joanette, Doyon, & Duchein, 1992; Benton Facial Recognition Test; Benton, Sivan, Hamsher, Varney, & Spreen, 1994). Finally, measures of *attentional and executive functions* were obtained from three DRS subtests (attentional, initiation/perseveration and conceptualization subtests) as well as from the Raven's Coloured Progressive Matrices that also offers a measure of nonverbal reasoning.

All participants performed normally on Raven's Coloured Progressive Matrices, whereas the majority was impaired on the DRS (9/10) and MMSE (7/10), as expected given the number of items testing vocabulary and comprehension in these two general cognitive functioning scales. Despite a day-to-day memory that was relatively spared at a clinical level, four of them failed on one of the three episodic memory tasks. However, only one participant scored below the normal range on one of the digit spans of working memory (SD4). The assessment of language abilities and semantic knowledge revealed a surface dyslexia when reading irregular words in 7/10 participants. Only one made errors when reading regular words. None of them were impaired on isolated word repetition. All participants exhibited compromised naming abilities (percentage of correct responses: mean = 35 ± 26.61%, range = 2.5-82.5%). Almost all scored below the normal range on both the verbal and visual semantic matching tasks (BECS-GRECO). Only one achieved normal scores on the visual semantic matching tasks. Visuoperceptual performance was normal for all participants (see Table 2 for individual performance on this neuropsychological battery). On attentional subtests, only one participant scored below the normal range (SD10). On initiation/perseveration and on conceptualization subtests, most participants with SD were impaired (respectively, 9/10 and 6/10), essentially owing to the involvement of lexical-semantic abilities in these subtests. Finally, all participants scored normally on the nonverbal reasoning task (Raven's Coloured Progressive Matrices).

Neuroimaging (MRI scans) revealed atrophy predominantly in the temporal lobes. This atrophy was bilateral, but more pronounced on the left side in six participants. The four others exhibited a more right-sided temporal atrophy (SD1; SD6; SD7; SD8). Seven participants (SD1, SD2, SD4, SD6, SD8, SD9, SD10) underwent a test for a cerebrospinal fluid (CSF) biomarker of AD, which showed that they all had a negative AD status.

Table 2. Individual neuropsychological data for each of the 10 patients with semantic dementia. Scores bolded were below normal range

| | | **Participants with semantic dementia** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Cut-off at 5%** | **Mean (standard deviation)** | **SD1** | **SD2** | **SD3** | **SD4** | **SD5** | **SD6** | **SD7** | **SD8** | **SD9** | **SD10** |
| **General cognitive functioning** | | | | | | | | | | | | |
| Mini-Mental State Examination, MMSE (/30) | *26* | 23.5 (3) | 26 | **21** | 27 | **22** | **24** | 28 | **24** | **23** | **22** | **18** |
| Raven's Coloured Progressive Matrices (/36) | *15* | 29.2 (4.34) | 27 | 35 | 33 | 34 | 30 | 28 | 28 | 20 | 30 | 27 |
| Dementia Rating Scale, total score (/144) | *136* | 108.7 (19.17) | **119** | **89** | **127** | **107** | **102** | 137 | **121** | **112** | **102** | **71** |
| Attention subtests (/37) | *32* | 34.6 (1.65) | 34 | 34 | 36 | 34 | 35 | 35 | 36 | 37 | 34 | **31** |
| Initiation/perseveration subtests (/37) | *31* | 22.8 (6.65) | **26** | **20** | **28** | **28** | **19** | 33 | **24** | **19** | **22** | **9** |
| Construction subtests (/6) | *4* | 5.9 (0.32) | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 5 | 6 | 6 |
| Conceptualization subtests (/39) | *33* | 27.7 (8.43) | 33 | **14** | 35 | **25** | **24** | 39 | **32** | 34 | **26** | **15** |
| Memory subtests (/25) | *21* | 17.7 (4.55) | **20** | **15** | 22 | **14** | **18** | 24 | 23 | **17** | **14** | **10** |
| **Nonverbal episodic memory** | | | | | | | | | | | | |
| La Ruche visuospatial learning task Immediate free recall–sum of the 5 trials (/50) | *16* | 30 (13.76) | 48 | 27 | 35 | - | - | 30 | **10** | - | - | - |
| La Ruche visuospatial learning task Immediate forced-choice recognition (/10) | *7* | 9.75 (0.5) | 10 | 9 | 10 | - | - | 10 | - | - | - | - |
| La Ruche visuospatial learning task Delayed free recall (/10) | *4* | 9 (1.41) | 10 | 7 | 10 | - | - | 9 | - | - | - | - |
| Delayed recall of Rey-Osterrieth complex figure–Form A (/36) | *5* | 13.17 (7.92) | 16 | 22.5 | - | - | - | 17.5 | 16 | | **2** | **5** |
| The Doors visual recognition task: Part A (/12) | *8* | 7.83 (4.26) | - | - | 11 | 10 | 12 | - | - | **3** | 9 | **2** |
| The Doors visual recognition task: Part B (/12) | *5* | 6.25 (0.96) | - | - | 5 | 7 | 7 | - | - | - | 6 | - |
| **Working memory** | | | | | | | | | | | | |
| Digit Span Forward (WAIS-R) (/9) | *4* | 5.6 (1.07) | 4 | 5 | 6 | 4 | 5 | 7 | 6 | 6 | 7 | 6 |
| Digit Span Backward (WAIS-R) (/8) | *3* | 3.6 (0.84) | 3 | 3 | 4 | **2** | 4 | 5 | 3 | 4 | 4 | 4 |
| **Language and semantic knowledge** | | | | | | | | | | | | |
| Irregular word reading test (/18) | *17* | 14.8 (2.48) | **15** | 17 | **16** | **13** | **13** | **16** | 18 | **13** | 17 | **10** |
| Regular word reading test (/18) | *17* | 17.8 (0.63) | 18 | 18 | 18 | **16** | 18 | 18 | 18 | 18 | 18 | 18 |
| Isolated word repetition test (Boston Diagnostic Aphasia Examination) (/10) | *9* | 9.8 (0.25) | 9.5 | 10 | 10 | 10 | 9.5 | 10 | 10 | 10 | 9.5 | 9.5 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Naming task (BECS-GRECO) (/40) | *35* | 14 (10.64) | **18** | **23** | **21** | **1** | **7** | **33** | **19** | **4** | **13** | **1** |
| Verbal semantic matching task (BECS-GRECO) (/40) | *38* | 29.7 (5.65) | **32** | **35** | **37** | **20** | **26** | **37** | **29** | **24** | **30** | **27** |
| Visual semantic matching task (BECS-GRECO) (/40) | *38* | 32.3 (5.68) | **32** | **37** | **37** | **29** | 39 | **37** | **32** | **26** | **33** | **21** |
| BECS-GRECO total score-sum of the 3 tasks (/120) | *111* | 76 (20.11) | 82 | 95 | 95 | 50 | 72 | 107 | 80 | 54 | 76 | 49 |
| **Visuoperceptual abilities** | | | | | | | | | | | | |
| Benton Facial Recognition Test (/54) | *38* | 46.6 (3.34) | 45 | 50 | 49 | 49 | 45 | 46 | 39 | 45 | 49 | 49 |
| Protocole d'Evaluation des Gnosies Visuelles Embedded figure task (/36) | *30* | 35.1 (1.1) | 35 | 36 | 35 | 36 | 36 | 34 | 36 | 34 | 33 | 36 |
| Copy of Rey-Osterrieth complex figure (/36) | *29* | 34.2 (2.2) | 36 | 36 | 35 | 35 | 33 | 36 | 36 | 30 | 31 | 34 |

### 2.1.2 Participants with Alzheimer's disease

Ten participants with AD were also recruited as a patient control group. All fulfilled the National Institute of Neurological and Communicative Disorders and Stroke–Alzheimer's Disease and Related Disorders Association (NINCDS–ADRDA) criteria (McKhann et al., 1984). Most of the participants (8/10) were right-handed and the two others were left-handed. Their neurological physical examination was unremarkable, and a clinical interview revealed no history of neurological or psychiatric disorders, or drug or alcohol abuse. The participants' complaints and cognitive profiles were dominated by episodic memory disorders. The AD diagnosis relied on both clinical signs, neuropsychological features and AD biomarkers (CSF-AD biomarkers or amyloid imaging). The biomarker analyses confirmed AD in all of them.

All participants underwent a short neuropsychological battery assessing their *general cognitive functioning* (GRECO French-language version of the Alzheimer's Disease Assessment Scale-cognitive subscale, ADAS-Cog; Puel & Hugonot-Diener, 1996; MMSE; Folstein et al., 1975) and their *naming abilities* (BECS-GRECO; Merck et al., 2011 or DO80, Deloche & Hannequin, 1997). Total scores on the two general cognitive functioning scales indicated that most participants (9/10) had mild AD, but one patient had a moderate level of severity (mean MMSE score = 23.7 ± 2.7, range = 19-29; mean ADAS-COG score = 29.1 ± 9.8, range = 13.67-46). The ADAS-Cog did not reveal any difficulty in understanding spoken language. Mild-to-moderate word finding difficulties were only observed in 3/10 participants, while one patient had a very minor difficulty with oral expression. The number of errors in naming objects and fingers was low (mean = 1.4 ± 1.5 errors, range = 0-4). On naming tasks, 4/10 participants with AD performed below normal range (percentage of correct responses for the AD group: mean = 90.25 ± 7.88%, range = 77.5-100%) and they were less impaired than the participants with SD ($t(18) = -6.621$, $p < 0.001$).

#### 2.1.3 Healthy controls

We also recruited 20 healthy older adults. All completed the forced-choice picture-matching task coupled with the MMSE (Folstein et al., 1975). They also underwent an extensive interview beforehand to ensure that they had no history of neurological or psychiatric disorders, or drug use.

One-way ANOVAs on demographic features revealed main effects of age ($F(2,39)= 4.572$, $p = 0.017$), years of education ($F(2,39) = 27.791$, $p < 0.001$) and MMSE score ($F(2,39) = 30.518$, $p < 0.001$) between groups. For age, post hoc analyses indicated no significant differences between participants with SD and either controls or participants with AD (Tukey's HSD tests, all *p*s > 0.1). Only participants with AD were older than controls (Tukey's HSD, $p = 0.013$). For level of education, post hoc analyses showed that controls had a higher level than each of the two patient groups (Tukey's HSD, all *p*s < 0.001), but the difference between participants with SD and AD did not reach significance (Tukey's HSD, $p = 0.068$), with only a trend toward a lower level for participants with AD. For the MMSE scores, the level of cognitive functioning of the participants with SD was equivalent to that of the participants with AD (Tukey's HSD, $p = 0.958$), and controls performed significantly better than each of the other two groups of participants (Tukey's HSD, all *p*s $< 0.001$). For sex, no differences were found between the three groups ($\chi^2(2) = 2.762$, $p = 0.251$) (see Table 1). Disease duration did not significantly differ between the AD and the SD groups ($t(18) = 0.605$, $p = 0.553$).

Given these results, we sought to determine the influence exerted by both age and level of education on the two dependent variables retained from our experimental task, that are accuracy and reaction times (RTs). Logistic regression indicated that overall accuracy was predicted by level of education (estimate = 0.049, z = 3.521, $p < 0.001$) but not by age (estimate = 0.009, z = 1.036, $p = 0.300$). Linear regression showed that the two variables were significant predictors of overall RTs (estimate education = -0.033, t = -15.46, $p < 0.001$; estimate age = 0.018, z = 12.46, $p < 0.001$). The significant variables were therefore included as covariates in subsequent accuracy and RTs analyses.

## 2.2 Experimental materials and design

The stimuli and procedure were the same as in previous studies (see Kalénine et al., 2009, and Kalénine & Buxbaum, 2016, for details). Stimuli were 240 black-and-white drawings. Forty-eight were target pictures, 96 were semantically related to the target pictures, either thematically or taxonomically, and 96 were neither semantically nor perceptually related to the target pictures. Of the target pictures, 24 represented natural objects and 24 represented artifacts. For each target picture, a taxonomically related picture and a thematically related picture were selected. Targets, taxonomic items and thematic items were compared on several confounding variables provided in the Lexique database (New, Pallier, Brysbaert, & Ferrand, 2004). No significant differences were found between the three types of items on lexical frequency, familiarity, age of acquisition and image agreement (for all one-way ANOVAs, $p$ = *ns*).

Ninety-six triads featuring a target picture, a related picture and a nonrelated picture were displayed. Two lists of 48 triads were elaborated. In one list, the related picture was taxonomically related to the target. In the other list, the related picture was thematically related to the target. Each target picture appeared twice, with a taxonomically related picture in one list and with a thematically related picture in the other (see Fig. 1 for examples of stimuli and trials). Based on the type of association (taxonomic vs. thematic) and the target's domain of knowledge (natural objects vs. artifacts), the 96 trials could be divided into four conditions: taxonomic-natural (taxo-N), taxonomic-artifact (taxo-A), thematic-natural (thema-N) and thematic-artifact (thema-A). Eight additional triads with different pictures pertaining to different semantic categories were designed for practice trials. Kalénine et al. (2009) provided normative ratings of the strength of semantic association between each target and its related picture. In their pilot work, 10 adults rated the associative strength of taxonomic and thematic triads on a 10-point scale ranging from 0 (*Not associated at all*) to 10 (*Very closely associated*). No differences were found between the means for each condition, $F(1, 46) = 0.666$, $p = 0.419$ (taxo-N = 7.05 ± 1.18; taxo-A = 6.78 ± 1.06; thema-N = 7.06 ± 1.27; thema-A = 7.22 ± 1.47). Nonetheless, as expected, perceptual similarity was higher in the two taxonomic conditions, $F(1, 46) = 35.311$, $p < 0.001$ (taxo-N = 4.59 ± 1.96; taxo-A = 4.42 ± 1.80) than in the two thematic ones (thema-N = 2.14 ± 1.22; thema-A = 2.54 ± 1.85).

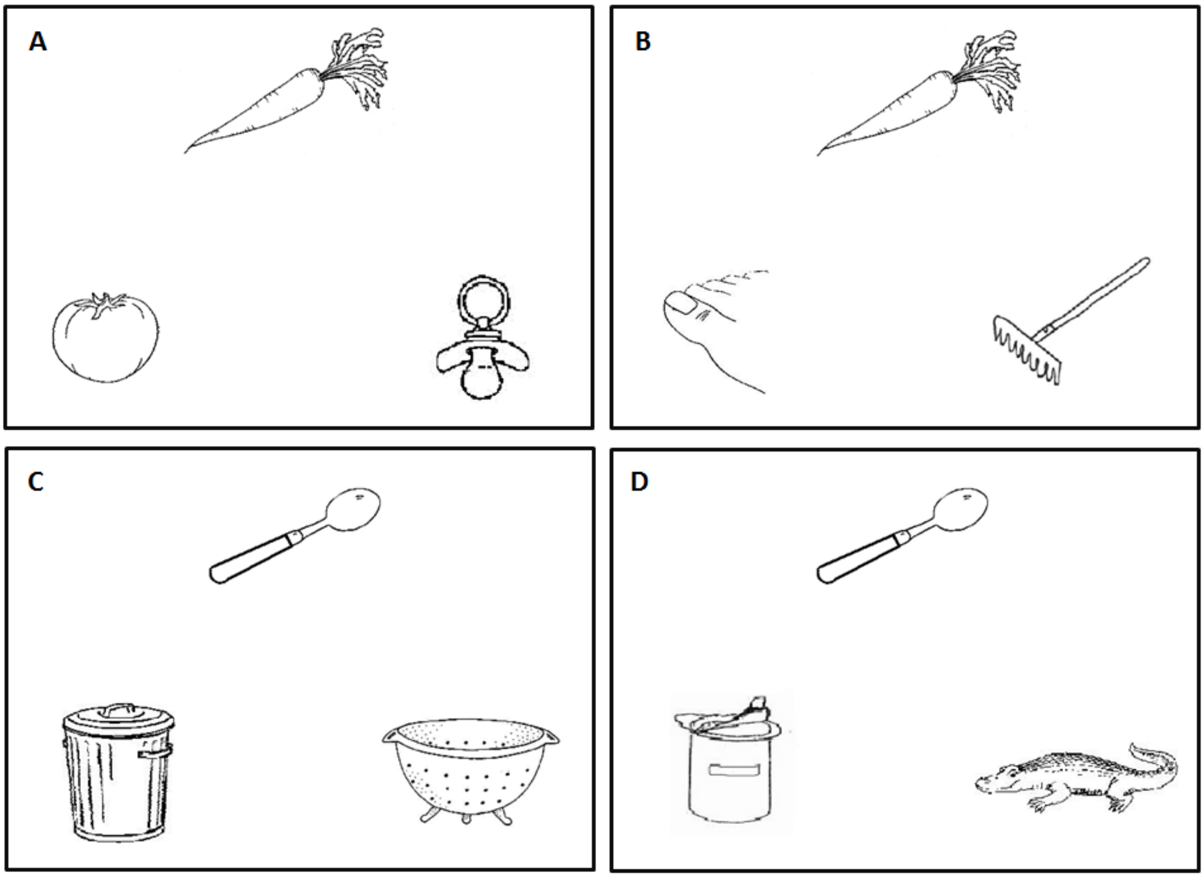


Figure 1. Examples of stimuli and trials used in the four conditions. (a and c) correspond to the taxonomic conditions ((a) for taxonomic-natural: carrot–tomato; (c) for taxonomic-artifact: spoon–colander).(b and d) depict the thematic conditions ((b) for thematic-natural: carrot–rake; (d) for thematic-artifact: spoon–yogurt).

Triads were displayed on a computer monitor using E-prime software (Psychology Software Tools Inc., Pittsburgh, PA, USA) and connected to an SR Box. Each trial began with a fixation cross for 500 ms, immediately followed by a picture triad. Target pictures appeared at the top of the screen. Related and nonrelated pictures were displayed at the bottom of the screen, on the left or right side, their relative position being counterbalanced across trials. Participants were asked to indicate which of these two bottom pictures was related to the top target picture, by pressing one of two buttons on the SR Box. They were instructed to press either 1 (bottom lefthand picture) or 2 (bottom righthand picture) with the index or middle finger their dominant hand. They were told to respond as quickly and accurately as possible. The triad was displayed until the participant responded. Each participant performed eight practice trials and then underwent the two lists of 48 trials each. The order of presentation of the two lists was counterbalanced across participants. Accuracy and RTs were recorded for all 96 experimental trials.

### 2.3 Statistical analyses

Analyses were carried out using R version 3.5.1. Logistic regression was carried out on accuracy data with Education (covariate), Group (two orthogonal contrasts: SD vs. AD and patients vs. controls), Relationship and Domain and their interactions as predictors using the *glm* and *lsmeans* functions. Odd ratio measures of effect size were obtained with the *logistic.display* function (*epiDisplay* package).

RTs were only analyzed for correct responses across the two semantic relationship conditions. Before the analysis, we removed extreme RTs, namely those below 500 ms, above 10000 ms, or more than three standard deviations above or below each participant's mean RT. We thus excluded 2.07% of total trials for healthy controls, 1.31% of total trials for the SD group, and 2.66% of total trials for the AD group. To ensure normality of distribution, we applied a logarithmic transformation on RTs. Linear regression was carried out on log-transformed RTs with Age and Education (covariates), Group (two orthogonal contrasts: SD vs. AD and patients vs. controls), Relationship and Domain and their interactions as predictors using the *lm* and *lsmeans* functions in R version 3.5.1. Cohen d measures of effect size were computed as the ratio between the estimated mean difference between conditions and the square root of the residual variance.

For all analyses, tests were two-tailed and the statistical level of significance was set at alpha = 0.05.

## 3. Results

### 3.1 Picture matching performance

#### *3.1.1 Accuracy*

On accuracy, the logistic regression analysis with level of education as covariate revealed a significant main effect of Group (contrast 1 [SD vs AD]: B = -0.826, z-value = -5.513, $p < 0.001$, odds ratio (OR) = 0.343; contrast 2 [patients vs. controls]: B = -2.03, z-value = -11.445, $p < 0.001$, OR= 0.214) with participants with SD showing the poorest performance (SD group: mean = 77.29 ± 18.90%; AD group: mean = 90.63 ± 4.91%; controls: mean = 96.20 ± 2.62%). There was also a significant main effect of Domain (B = -0.537, z-value = -4.258, $p < 0.001$, OR = 0.587) with overall performance for artifacts better than for natural entities (artifacts: mean = 92.24 ± 11.46%; natural entities: mean = 87,92 ± 14.68%), but no main significant effect of Relationship (B = -0.193, z-value = -1.532, $p = 0.125$, OR = 0.824; taxonomic: mean = 90.68 ± 14.86%; thematic: mean = 89.48 ± 11.62%). There was a trend towards significance for the Relationship x Domain interaction (B = -0.441, z-value = -1.749, $p = 0.080$, OR = 0.645), reflecting a greater advantage of taxonomic over thematic identification for natural compared to artifact objects overall. The Group x Relationship interaction was significant for the first Group contrast ([SD vs AD] x Relationship: B = 0.550, z-value = 1.968, $p = 0.049$, OR = 1.728), indicating that the greater performance of participants with AD compared to participants with SD was more important for taxonomic than for thematic relationships. There was no interaction between the second Group contrast and Relationship ([patients vs. controls] x Relationship: B = 0.123, z-value = 0.421, $p = 0.674$, OR = 1.131).

None of the Group x Domain interactions reached significance (Group contrast 1 x Domain: B = -0.015, z-value = -0.055, $p = 0.956$, OR = 0.994; Group contrast 2 x Domain: B = 0.147, z-value = 0.500, $p = 0.617$, OR = 1.164). The Group x Relationship x Domain interactions failed to reach significance (Group contrast 1 [SD vs AD] x Relationship x Domain: B = -0.142, z-value = -0.254, $p$ = 0.800, OR = 0.873; Group 2 [patients vs. controls] x Relationship x Domain: B = 0.413, z-value = 0.7104, $p$ = 0.481, OR = 1.518).

Paired comparisons between groups in each Domain x Relationship condition (with Tuckey adjustments) revealed that participants with SD differed from the other groups in two out of four conditions. In the taxo-N condition, they were less accurate than both controls (controls vs. SD: B = 2.638, z ratio = 8.870, $p < 0.001$) and participants with AD (AD vs. SD: B = 1.073, z ratio = 3.868, $p$ = 0.006). Participants with AD were also less accurate than controls (AD vs. controls: B = -1.566, z ratio = -4.358, $p < 0.001$). Similarly in the taxo-A condition, participants with SD were less accurate than both controls (controls vs. SD: B = 2.607, z ratio = 7.863, $p < 0.001$) and participants with AD (AD vs. SD: B =1.128, z ratio = 3.570, $p$ = 0.018). Participants with AD were also less accurate than controls (AD vs. controls: B = -1.478, z ratio = -3.629, $p$ = 0.015). In contrast in the thema-A condition, both participants with SD and participants with AD were less accurate than controls (controls vs. SD: B = 2.378, z ratio = 6.828, $p < 0.001$; AD vs. controls: B = -1.871, z ratio = -4.739, $p$ = 0.001). In addition, the two patient groups did not differ (AD vs. SD: B = 0.507, z ratio = 1.700, $p$ = 0.868). Similarly in the thema-N condition, both participants with SD and participants with AD were less accurate than controls (controls vs. SD: B = 2.072, z ratio = 8.357, $p < 0.001$; AD vs. controls: B = -1.478, z ratio = -5.077, $p < 0.001$), but the two patient groups did not differ (AD vs. SD: B = 0.593, z ratio = 2.456, $p$ = 0.368).

Paired comparisons between the four Domain x Relationship conditions in each group (with Tuckey adjustments) did not show any differences between conditions in the SD group (all $p$-values > 0.113), in the AD group (all $p$-values > 0.181), or in the control group (all $p$-values > 0.155).

To sum up, participants with SD differed from controls in all conditions and differed from participants with AD in the two taxonomic conditions but not in the two thematic conditions. Participants with AD differed from controls in all conditions. The mean scores of each group in each condition is presented in Table 3 and illustrated on Fig 2.

Table 3. Performance on the four conditions of the semantic matching task (Taxo-A: taxonomic–artifact; Taxo-N : taxonomic-natural; Thema-A: thematic-artifact; Thema-N: thematic-natural).
Accuracy was expressed as correct percent. Reactions times (RTs) were expressed in milliseconds and were calculated by averaging the correct trials.
* : significant difference between the patients with SD and the controls
§ : significant difference between the patients with AD and the controls
† : significant difference between the patients with SD and the patients with AD

| | | Taxo-A | Taxo-N | Thema-A | Thema-N |
|---|---|---|---|---|---|
| **Patients with semantic dementia** | **Accuracy (%)** Mean *(Standard Deviation)* | 79.17 (*20.69*) * † | 73.75 (*26.65*) * † | 83.75 (*14.63*) * | 72.5 (*16.22*) * † |
| | **RTs (ms)** Mean *(Standard Deviation)* | 3370.84 (*1794.50*) * | 3290.89 (*1729.02*) * | 3423.47 (1601.17) * | 4070.86 (*1952.85*) * |
| **Patients with Alzheimer's disease** | **Accuracy (%)** Mean *(Standard Deviation)* | 93.75 (*6.87*) † | 91.25 (*6.35*) † | 91.67 (*3.93*) § | 85.83 (*8.15*) § † |
| | **RTs (ms)** Mean *(Standard Deviation)* | 3021.79 (*2087.99*) § | 3106.29 (*2094*) § | 2900.78 (*1773.09*) § | 3445.42 (*2024.96*) § |
| **Healthy controls** | **Accuracy (%)** Mean *(Standard Deviation)* | 97.29 (*3.65*) * | 96.46 (*4.12*) * | 97.5 (*3.68*) * § | 93.54 (*4.38*) * § |
| | **RTs (ms)** Mean *(Standard Deviation)* | 1911.48 (*778.68*) * § | 1828.42 (*767.64*) * § | 1850.41 (*775.36*) * § | 2016.81 (*771.15*) * § |

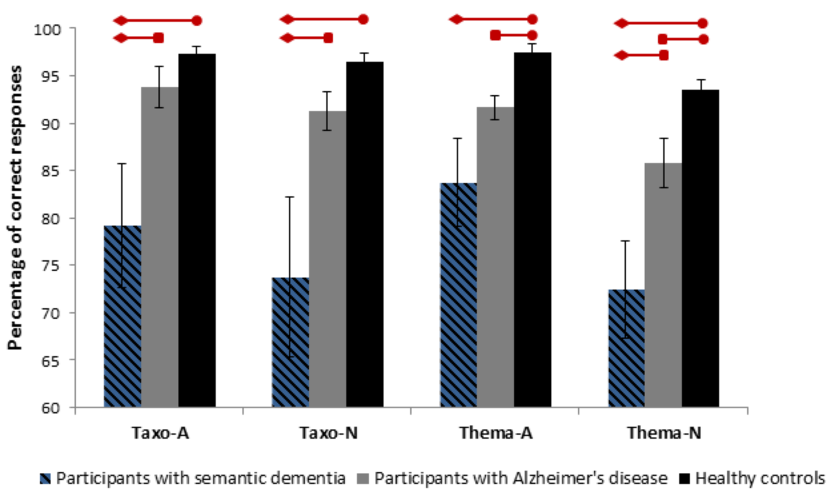

Figure 2. Participants' accuracy in each condition of the forced-choice picture matching task. Mean performance is expressed as the percentage of correct responses for each of the four semantic conditions (taxo-A: taxonomic–artifact; taxo-N: taxonomic-natural; thema-A: thematic-artifact; thema-N: thematic-natural).Error bars represent the standard error of the mean.Horizontal bars indicate significant planned between-group comparisons. The symbols at the ends of the bars mean: for diamond, a difference between SD group and another group; for square, a difference between AD group and another group; for circle, a difference between healthy controls and another group.

Through additional analyses, we further investigated the particular status of thematic relationships by comparing the patterns of correlations (Spearman's rho) between conditions in each group. In the controls, only thema-A performance correlated with taxo-N performance (correlations between scores in thema-A and taxo-N: $\rho = 0.641, p = 0.002$; thema-A and taxo-A: $\rho = 0.364, p = 0.115$; thema-A and thema-N: $\rho = 0.059, p = 0.805$; taxo-A and taxo-N: $\rho = 0.339$, $p = 0.144$; thema-N and taxo-N: $\rho = 0.208$, $p = 0.380$; thema-N and taxo-A: $\rho = 0.141$, $p = 0.552$). In the AD group, thematic performance correlated with taxonomic performance within each domain of knowledge (correlations between scores in thema-N and taxo-N: $\rho = 0.908, p < 0.001$; thema-A and taxo-A: $\rho = 0.802, p = 0.005$; thema-A and taxo-N: $\rho = 0.249, p = 0.488$; thema-N and taxo-A: $\rho = 0.447, p = 0.196$; thema-A and thema-N: $\rho = 0.342, p = 0.334$; taxo-A and taxo-N: $\rho = 0.403, p = 0.249$). In the SD group, performance correlated between conditions overall, apart from thema-A performance that was independent from taxonomic performance. Thema A performance was only significantly related to thema-N performance (correlations between scores in thema-N and thema-A: $\rho = 0.741, p = 0.014$; thema-N and taxo-N: $\rho = 0.788, p = 0.007$; thema-N and taxo-A: $\rho = 0.680, p = 0.031$; thema-

A and taxo-N: $\rho = 0.529$, $p = 0.116$; thema-A and taxo-A: $\rho = 0.592$, $p = 0.071$; taxo-A and taxo-N: $\rho = 0.726$, $p = 0.017$).

Moreover, when computing correlations in the SD group between the total score on the BECS-GRECO semantic battery and performance in each of the four conditions of the experimental matching task, we found significant correlations for all conditions except for thema-A (correlations between the total BECS-GRECO scores and taxo-A: $\rho = 0.640$, $p = 0.046$; taxo-N: $\rho = 0.878$, $p = 0.001$; thema-N: $\rho = 0.810$, $p = 0.004$; thema-A: $\rho = 0.421$, $p = 0.226$). Together, the correlation results emphasized and specified the particular status of thematic knowledge in the SD group, which seems particularly driven by artifact concepts.

Considering the absence of significant correlation between thema-A performance and performance in the two taxonomic conditions in the SD group, we wanted to investigate the existence of dissociations between thema-A and taxonomic performance at an individual level, for each participant with SD. To this aim, we directly compared thema-A versus taxo-N performance. This choice was based on the assumption that natural entities are more relevant for assessing taxonomic processing, while artifacts appear more suited to measuring thematic processing (Cree & McRae, 2003; McRae et al., 2005). One should remind that the scores in these two conditions were the only ones that were correlated in controls (taxo-N scores positively correlated with thema-A scores: $\rho = 0.641$, $p = 0.002$). We compared the performance of participants with SD in these two conditions and assessed whether their performance profile was influenced by the severity of their disease. To this end, we looked at whether this difference increased as the disease progressed. We ranked these participants according to their level of semantic impairment, as measured by the total score on the BECS-GRECO semantic battery (see Fig. 3). For each participant, we measured the dissociation between the two conditions (thema-A vs. taxo-N) using the Bayesian criterion for dissociations in case studies, associated with the Bayesian standardized difference test (BSDT) developed by

Crawford, Garthwaite, and Porter (2010). This procedure allowed us identify *strong dissociations* (i.e., significant standardized difference between individual's scores in X and Y conditions, and significant deficit in at least one of these two conditions), providing the two scores were sufficiently correlated in the control group. Significant dissociations appeared for the four participants with the most pronounced level of semantic impairment, with far better performance in the thema-A condition than in the taxo-N condition (SD10: semantic battery score = 40.83%; BSDT, $Z\text{-}D_{CC} = -9.245$, $p = 0.005$; SD4: semantic battery score = 41.67%; BSDT, $Z\text{-}D_{CC} = -5.558$, $p < 0.001$; SD8: semantic battery score = 45%; BSDT, $Z\text{-}D_{CC} = -6.819$, $p = 0.025$; and SD5: semantic battery score = 60%; BSDT, $Z\text{-}D_{CC} = -5.845$, $p < 0.001$). Besides, SD4's and SD5's thema-A scores did not differ significantly from those of controls. In the AD group, we found that only one participant presented the same dissociation as the four participants with SD (BSDT, $Z\text{-}D_{CC} = -3{,}131$, $p = 0.01$) whereas two others showed the reverse dissociation (BSDT, $Z\text{-}D_{CC} = 3{,}222$, $p = 0.01$; BSDT, $Z\text{-}D_{CC} = 4{,}287$, $p < 0.001$). Despite their opposite patterns of dissociation, these three participants with AD had an equivalent level of general cognitive functioning (MMSE scores: 22, 22 and 23). Besides, the three participants were situated below the median of the AD group on naming performance (confrontation naming scores, percentage of correct responses = 77.5%, 85%, 88.75%; AD group: median = 90.63%). In the AD group, taxonomic/thematic dissociations were thus more heterogeneous than in the SD group and were not influenced by the severity of the disease.

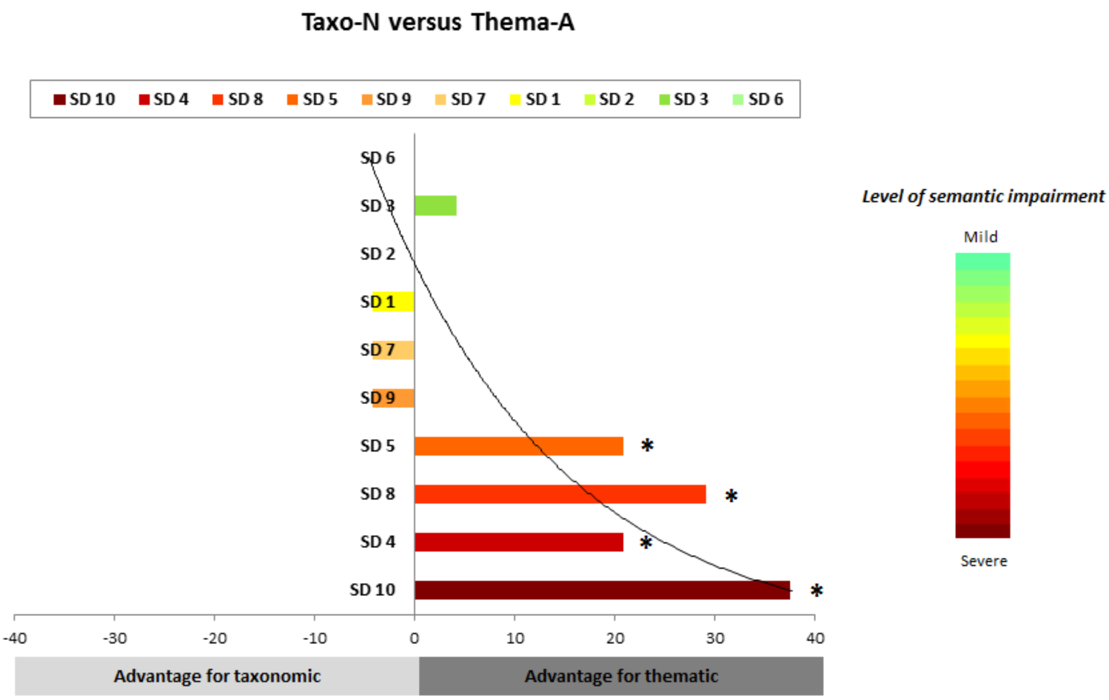


Figure 3. Distribution of participants with SD according to the difference in scores between the taxonomic-natural (taxo-N) and thematic-artifact (thema-A) conditions.The color (gray) gradient along the y-axis indicates the severity of the disease, from green (light gray) (for mild semantic impairment) to dark red (dark gray) (for severe semantic impairment).A colored (gray) bar to the left of the y-axis means that the difference favored the taxonomic-natural condition over the thematic-artifact one. A colored (gray) bar to the right of the y-axis means that the difference favored the thematic-artifact condition over the taxonomic-natural one.The curve represents the logarithmic tendency for the distribution of the difference score (i.e., taxo-N vs. thema-A).Asterisks indicate significant and strong dissociations between the two conditions, measured with the Bayesian criterion for dissociations in case studies, associated with the Bayesian standardized difference test developed by Crawford et al. (2010).

### *3.1.2 Reaction times (RTs)*

On reaction times, the linear regression analysis with age and level of education as covariates revealed a significant main effect of group (contrast 1 [SD vs AD]: B = 0.229, t-value = 9.213, $p < 0.001$, d = 0.548; contrast 2 [patients vs. controls]: B = 0.451, t-value = 16.592, $p < 0.001$, d = 1.078) with participants with SD being the slowest (SD: mean = 3522.72 ± 1785.83 ms; AD: 3114.36 ± 2003.80 ms; controls mean = 1900.35 ± 775.62 ms). There was also a significant main effect of Domain (B = 0.060, t-value = 3.592, $p < 0.001$, d = 0.144) with faster response times for artifacts than for natural entities (artifacts: mean = 2456.54 ± 1503.49 ms; natural entities: mean = 2573.53 ± 1618.64 ms), and a significant main effect of Relationship (B = 0.079, t-value = 4.692, $p < 0.001$, d = 0.188) with overall faster response times for taxonomic than for thematic relations (taxonomic: mean = 2446.11 ± 1561.02; thematic: mean = 2579.05 ± 1557.76 ms). There was a significant Relationship x Domain interaction (B = 0.161, t-value = 4.802, $p < 0.001$, d = 0.386), reflecting a greater advantage of taxonomic over thematic identification for natural compared to artifact objects overall. The Group x Relationship interaction was significant for the second Group contrast ([patients vs. controls] x Relationship: B = 0.062, t-value = 2.016 $p = 0.043$, d = 0.149), indicating that the advantage of taxonomic over thematic identification was more pronounced for patients than for controls. There was no interaction between the first Group contrast and Relationship ([SD vs. AD] x Relationship: B = 0.073, t-value = 1.592, $p = 0.111$, d = 0.176).

There was also a trend towards significance for the Group x Domain interaction for the second Group contrast ([patients vs. controls] x Domain: B = 0.059, t-value = 1.907, $p = 0.057$, d = 0.141) indicating a greater advantage of artifact over natural entities that was more pronounced for patients than for controls, but no significant Group x Domain interaction for the first Group contrast ( [SD vs AD] x Domain: B = -0.019, t-value = 1.907, $p = 0.678$, d = 0.046). The Group x Relationship x Domain interactions failed to reach significance (Group contrast 1 [SD vs AD] x Relationship x Domain: B = 0.1018, t-value = 0.092, $p = 0.201$, d = 0.044; Group 2 [patients vs. controls] x Relationship x Domain: B = 0.034, t-value = 0.547, $p = 0.584$, d = 0.081).

Paired comparisons between groups in each Domain x Relationship condition (with Tuckey adjustments) showed that the three groups systematically differed on response times, regardless of the condition (all $p$-values $< 0.01$), with participants with SD being always slower than participants with AD and controls, and participants with AD being always slower than controls.

Paired comparisons between the four Domain x Relationship conditions in each group (with Tuckey adjustments) showed that the thema-N condition was the slowest condition in patients, and to a certain extent in controls. In the SD group, the thema-N condition was slower than the others (all $p$-values $< 0.046$), which did not differ (all $p$-values $> 0.97$). It was the same pattern in the AD group, the thema-N condition was slower than the others (all $p$-values $< 0.047$), which did not differ (all $p$-values $= 1$). In the control group, thema-N significantly differed from taxo-N ($p = 0.012$) and at the trend level from thema-F ($p = 0.066$); the other conditions did not differ (all $p$-values $> 0.650$).

To sum up, we found longer RTs when identifying thematic relationships for natural entities overall, without distinction between the SD and AD groups.

## 4. Discussion

The present study investigated the ability to identify taxonomic and thematic relationships as a function of object domain (natural or artifact) in participants with SD, compared with participants with AD and controls. We showed that thematic knowledge had a particular status in the SD group. On accuracy, we demonstrated that participants with SD differed from participants with AD in the taxonomic conditions, but not in the thematic conditions. Furthermore, additional analyses on accuracy in the SD group showed that performance for the identification of thematic relationships for artifacts was independent from taxonomic performance. Moreover, the degree of semantic breakdown (as measured by the

BECS-GRECO semantic battery) correlated with the ability to identify all types of semantic relationships except thematic relationships for artifacts. Taken together, thematic knowledge – especially when it concerns artifacts - seems to follow a different trajectory from the other types of knowledge and to remain relatively preserved from the massive semantic erosion that takes place in participants with SD. This finding provides evidence for heterogeneous disruptions of semantic knowledge in SD, and highlights another type of performance dissociation, in addition to the well-known verbal/nonverbal input modality dissociation (Gainotti, 2017, 2018; Snowden et al., 2012, 2017), the reversal of the concreteness effect (Breedin et al., 1994; Joubert et al., 2017; Macoir, 2009 ; Reilly et al., 2007; Yi et al., 2007), the previously demonstrated category-specific effect (Merck et al., 2013, 2017), and the difference in the level of feature impairment (Hoffman, Jones, & Ralph, 2012; Lambon Ralph, Patterson, Garrard, & Hodges, 2003; see also Gainotti, 2017). Our results therefore add another level of distinction, this time between types of semantic relationships, with thematic relationships being more resistant to the disease. This finding once again questions the view of an all-or-nothing semantic breakdown in this disorder. Instead, our results support the notion of more fine-grained distinctions in the profile of participants with SD, depending among others on the type of semantic knowledge being considered.

Paradoxically, similar performance profiles have already been reported in a group of participants with AD (Simoes Loureiro & Lefebvre, 2016), suggesting that the dissociation may not be unique to SD. These authors divided participants with AD into three groups according to the severity of their disease. In their first experiment, participants performed a naming task where object pictures were embedded in a semantic priming paradigm. In the control group, they highlighted a significant priming effect for taxonomic relationships, but no effect for thematic relationships. The mild and moderate AD groups showed significant priming effects in both conditions, although the magnitude of the thematic priming effect in the mild AD group was closer to that of controls. Their second experimental task consisted of an explicit card-sorting task, where participants were instructed to preferentially sort a target picture with either a taxonomically related picture, a thematically related picture, or an unrelated picture. The authors observed that the participants with AD chose the thematically related picture more frequently, and concluded that taxonomic relationships undergo an earlier impairment, while thematic relationships are more resistant to semantic deterioration. The profile of the participants with SD in our study was therefore similar to that of their participants with AD, although we failed to replicate the latter's pattern of results in our own AD group. On the contrary, when considering their accuracy, we demonstrated that participants with AD were impaired in both taxonomic and thematic conditions but they presented better performance for taxonomic than for thematic relationships compared to participants with SD. There are two possible explanations for these contradictory findings. First, Simoes Loureiro and Lefebvre (2016) underlined that their participants with AD were very old, and certainly a great deal older that ours (more than a decade older on average). Age has been shown to be major factor to consider when studying the AD syndrome. It has recently been demonstrated that AD rarely occurs in isolation (9%) in old age, but instead with mixed neuropathologies, and accounts on average for about 50% of the observed cognitive loss (Boyle et al., 2018). The patterns of atrophy have also been shown to vary with age, with greater volume loss in posterior and posteromedial regions in younger patients with AD (Fiford et al., 2018). The cognitive expression of AD in old age may thus be different from that in younger patients. Second, Simoes Loureiro and Lefebvre (2016) emphasized that they could not rule out a task effect to explain their findings. On this point, there was a major difference between the two studies, in terms of the general aims of the explicit tasks. The paradigm adopted in our study was designed to assess the ability to identify a semantic relationship between a target and a related picture in two separate conditions (taxonomic and thematic), rather than to establish an explicit preference for one or other of these relationships. These methodological differences make it hard to strictly compare the two studies, as they yielded differential information, depending on the processing induced by the experimental condition. When we separately assessed explicit taxonomic and thematic processing, results pointed toward a weaker ability to identify thematic than taxonomic relationships in AD compared to SD.

An extensive review of the literature on thematic and taxonomic processing in behavioral, event-related potentials (ERP) and fMRI studies in healthy adults, as well as voxel-based lesion–symptom mapping studies in participants with stroke, highlighted several findings that could account for the particular status of thematic knowledge in SD. First, thematic processing was frequently reported as being less effortful and therefore preferred over taxonomic processing. In a free classification task of familiar objects, participants sorted objects thematically more frequently than taxonomically (Lawson, Chang, & Wills, 2017), and students were also found to prefer thematic relationships, when required to choose between these two types of categorization (Lin & Murphy, 2001). Moreover, Kotz, Cappa, von Cramon, and Friederici (2002) demonstrated that healthy adults are slower to respond to taxonomic relationships than to thematic relationships, and Sachs et al. (2008) found larger priming effects in a thematic condition than in a taxonomic one, together with more errors for taxonomic relationships. Sass, Sachs, Krach, and Kircher (2009)'s priming study also reported clearer results in favor of thematic processes in healthy adults, as they only found a significant priming effect in the thematic condition, and no priming effect for taxonomic relationships. Nonetheless, Kalénine et al. (2009, 2016) nuanced these results, indicating that the preference for thematic relationships is above all valid for manufactured objects. Moreover, while thematic processing is often regarded as less effortful, Geller, Landrigan, and Mirman (2019) emphasized the importance to consider the strength of the semantic relationship. The cognitive control requirement is mainly determined by the strength of the semantic relationship rather than the type of semantic relationship. Despites some discrepancies, a similar interpretation has been also formulated by Thompson et al. (2017). The authors demonstrated that weak thematic relationships involved greater executive/semantic control than strong thematic relationships to retrieve the contextual information that is required to identify complementary-based relationships. Second, when the temporal dynamics of EEG signals are analyzed in ERP and event-related spectral perturbation studies, thematic processing turns out to be easier than taxonomic processing. In a word-image verification task, Savic, Savic, and Kovic (2017) revealed distinct EEG signal patterns for N400 and P600 when the prime was taxonomically versus thematically related to the target. The thematic relationship elicited less negativity on the N400 effect while the taxonomic one engaged higher P600 modulation in a late temporal window. Maguire et al. (2010) previously failed to report any difference between the two types of semantic processing on N400, but demonstrated differential spectral responses, in that theta power increased over right frontal areas for thematic processing, and alpha power increased over parietal areas for taxonomic processing. These results suggest that taxonomic relationships involved additional inhibitory and attention mechanisms. Similarly, Jackson et al. (2015) found only minor frontal differences when they contrasted taxonomic and thematic processing, and these differences disappeared when the authors controlled for RTs. Overall, despite the discrepancies in the neural locus of the effect, it could be argued on the basis of these studies that taxonomic processing is more difficult and/or involves greater cognitive demands than thematic processing. Thus, one possible explanation is that our participants with SD simply displayed preserved performance in the easiest semantic condition (i.e., identification of thematic relationships). This interpretation would be compatible with the "hub and spoke" model of semantic memory (Lambon Ralph et al., 2010; Patterson et al., 2007; Rogers et al., 2004). The "hub and spoke" model predicts relatively subtle differences between taxonomic and thematic processing, as taxonomic and thematic relationships would both be represented within a single, unified semantic system that heavily rely on the anterior temporal lobes (Jackson et al., 2015; Lambon Ralph et al., 2017; Rice et al., 2015). However, it is relatively unlikely that participants with SD showed preserved performance in the easiest thematic condition. First, across conditions, semantic relations were carefully controlled and matched on the strength of the semantic association (see Section 2 “Materials and methods”). Second, there were no differences in the accuracy of healthy controls between the identification of thematic relationships and the identification of taxonomic relationships for artifacts or natural objects. Third, participants with SD and participants with AD, that were strictly matched on demographic features and on disease duration, exhibited different performance patterns, especially when we compared conditions that appeared to be of equal difficulty for healthy controls (e.g., taxonomic-natural and thematic-artifact). Instead, we believe that the profile exhibited by participants with SD points to substantial qualitative differences between taxonomic and thematic processing that go beyond task difficulty.

Although it is unlikely that the result pattern reported here merely reflect the processing of semantic relations at different levels of difficulty, the role of general executive functions in taxonomic and thematic processing remains to clarify. We acknowledge that the limited assessment of attentional/executive functions and, notably, the absence of measure of cognitive flexibility in our study as well as the differences in the neuropsychological batteries administered to participants with SD and participants with AD constitute limitations to the present study. In a longitudinal study, Smits et al. (2015) demonstrated a decline in executive functions for the participants with the language variant of frontotemporal dementia (lvDFT, including both 8 participants with SD and 7 non-fluent progressive aphasia participants). One could thus argue that the profile of participants with SD with the most pronounced level of semantic impairment may be related to important executive disturbances, which increase with the evolution of the disease. However, in the Smits et al. (2015)’s study, the participants with

AD were initially more impaired on attention and on executive functioning than the participants with lvDFT and they also showed a significant decline of this cognitive domain. If the better performance for thematic identification in the participants with SD was due to a lesser executive demand in the thematic conditions than in the taxonomic conditions, one should expect the same pattern of performance in the AD group. However, that was not the case in the present study, as the participants with AD presented greater accuracy for taxonomic than for thematic relationships compared to participants with SD, with a pattern of correlations between conditions different from that of participants with SD. Moreover, the evaluation of dissociations between the taxonomic-natural versus thematic-artifact conditions revealed more heterogeneous patterns in the AD group, which were not clearly influenced by the severity of the disease. Executive functions may thus play an undetermined role in our semantic matching task but may not be entirely responsible for the relatively preserved identification of thematic relationships in the SD group. Instead, the pattern of results observed point to differences in the semantic processing involved in taxonomic and thematic knowledge.

This interpretation is consistent with another important line of evidence supporting at least partially distinct neural mechanisms for taxonomic and thematic relationships (de Zubicaray et al., 2013; Kalénine et al., 2009; Kalénine & Buxbaum, 2016; Lewis et al., 2015; Mirman & Graziano, 2012; Schwartz et al., 2011; Xu et al., 2018). In particular, several neuroimaging studies in healthy controls and lesion-symptom mapping studies in patients have demonstrated that, compared with taxonomic relationships, which mostly rely on the anterior temporal lobe, thematic relationships recruit posterior regions around the temporoparietal junction (de Zubicaray et al., 2013; Kalénine et al., 2009, Kalénine & Buxbaum, 2016; Mirman & Graziano, 2012; Schwartz et al., 2011; Xu et al., 2018). The temporoparietal junction is known to be relatively spared in SD (Brambati et al., 2015; Bright et al., 2008; Chan et al., 2001; Desgranges et al., 2007; La Joie et al., 2014; Leyton et al., 2016). Moreover, abnormalities in this area have been identified as specific and sensitive markers of the presence of AD pathology (Whitwell et al., 2011). Thus, the different degrees of damage to posterior temporoparietal areas in AD versus SD could account for participants' different performance profiles in the identification of thematic relationships.

Hurley, Mesulam, Sridhar, Rogalski, and Thompson (2018) recently added another area to the brain network involved in thematic processing. They demonstrated that the performance of participants with SD on a picture-based thematic verification task was correlated with the cortical thickness of the right ATL. They also observed that the most salient difference between participants with higher versus lower performance was atrophy in the right ATL. Nonetheless, Figure 3 of their paper (p. 97) suggests that participants with poorer scores on thematic verification presented more extensive brain abnormalities, including in the temporoparietal junction. This raises the question of whether this correlation with the right ATL was actually a reflection of more pronounced atrophy spreading to both the contralateral and posterior areas, as previously shown in longitudinal studies in SD (Brambati et al., 2015; Kumfor et al., 2016). In our study, the size of the SD group was unfortunately too small to allow testing the influence of the side of the temporal atrophy on the particular status of the thematic relationship. Nevertheless, we could point out that out of four participants with SD who exhibited a strong dissociation in favor of thematic relationships, only one of them (SD8) had right-sided temporal atrophy. Left/right asymmetries in participants' brain atrophy may thus not be responsible in themselves for the pattern of dissociation between taxonomic and thematic identification.

Moreover, the particular status of thematic relationship reported in the participants with SD appeared more patent for artifacts than for natural entities. Their accuracy in the thematic artifact condition was independent from their taxonomic performance and did not correlate with their level of semantic impairment (as measured by the BECS-GRECO semantic battery). Besides, participants with SD's identification of semantic relationships were the slowest in the thematic natural condition, as for the other participants. These refinements may come from the intrinsic constitution of artifact concepts, with complementary-based / thematic relationships being more important for this domain than for natural objects. When they administered the same experimental task to healthy adults and participants with stroke, Kalénine and colleagues (2009, 2016) reported an advantage for the identification of taxonomic over thematic relationships for natural objects and the opposite pattern for artifacts. The influence of the domain of knowledge was considered to be in keeping with SFT (Warrington & Shallice, 1984). This theoretical account assumes that semantic memory is divided into two subsystems, where knowledge about concepts is topographically organized according to the properties that are most distinctive for a given domain (natural entities vs. artifacts). More specifically, SFT states that the identification of living entities depends mainly on sensory features, whereas functional features are critical for the representation of nonliving items. We noted earlier that perceptual features have been shown to be a core determinant of similarity-based / taxonomic relationships, whereas complementary-based / thematic processing relies mainly on contextual relationships (Denney, 1975; Estes et al., 2011; Lin & Murphy, 2001; McRae et al., 1997, 2005; Medin & Ortony, 1989), meaning that the particular status of thematic processing more patent for artifacts than for natural entities in the SD group could fit into the SFT framework. Other results consistent with these predictions were the greater advantage of taxonomic over thematic identification for natural compared to artifact objects overall when considering accuracy regardless of group, together with the slowest identification of thematic relationships for natural entities in the three groups of participants.

Based on the SFT framework, we then explored differences between the two semantic relationships according to the domain of knowledge that was most relevant for each relationship (i.e., thematic-artifact vs. taxonomic-natural conditions) at the individual level. When we compared the performance of participants with SD in the thematic-artifact versus taxonomic-natural conditions, we found a strong dissociation for the four participants with the most advanced disease. This dissociation was not obvious in the participants with AD. All four SD participants scored far better on the identification of thematic relationships for artifacts than on the identification of taxonomic relationships for natural objects. The consideration of the level of severity of the disease and of the subtle influence of the domain of knowledge may explain the apparent divergence with Hoffman et al. (2013)'s results. When the authors administered a forced-choice word-matching task to six participants with SD, they failed to find any differences between the taxonomic and thematic conditions for the whole item set, but did not take into account these two factors.

This dissociation observed at the more severe level of the disease may also refuel the discussion about a presumed semantic disequilibrium in SD. In a prior study using a priming paradigm associated with a lexical-decision task (Merck et al., 2014), the authors found a significant priming effect for visuoperceptual features in controls, but no such effect for contextual-functional features, supporting the notion that similarity-based / taxonomic relationships have an advantage over complementary-based / thematic relationships in healthy participants. In participants with SD, the deterioration of visuoperceptual attributes impeded the similarity-based / taxonomic processes, and thus brought complementary-based / thematic relationships to the fore. The authors thus hypothesized that these two semantic processes are held in balance, with the spared process (thematic processing in SD) taking over from the impaired process (taxonomic processing in SD). To some extent, the notion of a balance between two types of semantic relationship was also supported by Kalénine, Mirman, and Buxbaum (2012)'s study, which showed a negative correlation between the implicit processing of thematic relationships (e.g., saw-wood) and relationships of general functional similarities (e.g., saw-drill) in participants with stroke. In the present study, we reported a significant and positive relation between the severity of the semantic impairment and performance on the identification of taxonomic relationships for natural objects, but no relation between semantic impairment severity and thematic performance for artifacts. We also noticed that performance for thematic-artifact did not correlate with any of the taxonomic conditions. Although the absence of a correlation between taxonomic and thematic performance is not fully consistent with the semantic disequilibrium hypothesis, the pattern of correlations confirmed that participants with SD have relatively preserved access to some semantic knowledge that is not separately evaluated in the classic neuropsychological assessment. This highlights the relevance of including more specific semantic tests in patient assessments, in order to capture the different types and modalities of knowledge.

Other experimental paradigms might be better suited to further investigating the notion of a semantic disequilibrium between the two semantic processes and to further reduce the intervention of non-semantic cognitive functions. It is well known that explicit semantic matching tasks may be contaminated by additional mechanisms. These tasks may be correctly achieved by patients even though their choices are justified by aberrant reasoning (e.g., extracted from our practice with a patient with SD: "turtle goes with salad because we can make turtle salads"). Some patients were also found to rely on immediate perceptual features (e.g., size of the pictures being presented) to match objects. To reduce intentional processes and promote automatic access to semantic knowledge, implicit approaches are recommended. Merck et al. (2014) previously opted for a lexical-decision priming paradigm to assess two different types of attributes: visuoperceptual versus contextual-functional. Unfortunately, this paradigm cannot measure implicit and independent processing of taxonomic and thematic relationships in SD, as hyperpriming effects have frequently been reported when the two concepts that are presented share a coordinated relation (Giffard et al., 2001, 2002; Laisney et al., 2011), owing to the extinction of their distinctive attributes. For example, *tiger* primed *lion*, because the *tiger lost its stripes* and the *lion, its mane*, meaning that the remaining spared features were shared by both entities and entirely overlapped, leading to confusion between the two concepts. Moreover, Laisney et al. (2011) claimed that hyperpriming effects only occur during a specific time window along the semantic deterioration trajectory. When the semantic deterioration of patients matches this time window, the interpretation of priming results become highly debatable in the case of a direct comparison between the two semantic relationships, as a hyperpriming effect for the taxonomic relationship could supplant any priming effect for the thematic one. The report of a relatively preserved taxonomic priming effect in AD in Simoes Loureiro and Lefebvre (2016)'s study might thus have been misleading, had the results of the explicit matching task not been taken into account.

Future studies will have to look for relevant paradigms to investigate fine-grained differences between implicit taxonomic and thematic processing in SD.

In conclusion, we provide evidence that participants with SD differentially identify taxonomic and thematic relationships. We report a particular status of thematic relationships, particularly driven by artifacts, owing to the inherent constitution of artifact concepts. We also prove that this performance profile is specific to SD, as it was not found in participants with AD. Overall, the present findings are consistent with the existence of two functionally and anatomically distinct semantic systems.

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