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ORIGINAL ARTICLE

Analyzing lexical-semantic networks in Alzheimer's disease patients: eye-tracking study

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Abstract
Adults have an interconnected lexicon in which two words are related because their referents belong to the same semantic category, because they occur in the same context, or both. This interconnection has been explored by means of the priming effect, in which people respond more rapidly to related than to unrelated words and benefit from the lexical boost when the two types of interconnections are combined. Although substantial research has reported on the memory problems of people diagnosed with Alzheimer's disease (AD), it remains unknown whether they experience problems with related words at these levels of comprehension. This study analyzed the lexical networks of older adults with AD and typically aging (TA) adults to understand their semantic memory related to word associations. We tested combined taxonomic-thematic, purely taxonomic, and purely thematic relationships using an eye tracker to analyze fixations to a named target picture preceded by a related or unrelated prime word. Participants with TA showed a priming effect in all three types of relationships, but those with AD showed this effect only with purely thematic pairs. Words that share more than one level of relationship seem to create competition, revealing a deficit in the lexical networks of people with AD.

Keywords: Adult language disorders; aging and language; Alzheimer's and dementia; lexical processing; memory and language

Introduction

Alzheimer's disease (AD) is a neurocognitive disorder that accounts for 60%–80% of cases of dementia. Age is the most significant risk factor: people who develop AD tend to be over 65 years old. It is estimated that by 2050, the number of people with AD will triple (Alzheimer's Association, 2020; Mayo Clinic, 2022; World Health Organization, 2021). AD progresses slowly from mild memory loss to dementia, owing to the formation of amyloid plaques in the hippocampus and entorhinal

cortex, located in the middle temporal lobe, and spreading later to the posterior temporal, parietal, occipital, and frontal lobes (Smith, 2002). People with AD experience memory loss and cognitive impairments that affect daily life, with deficits in visuospatial skills and executive functions, and psychological and behavioral changes (Pradilla, 2004). AD is characterized neuropathologically by neurofibrillary tangles and amyloid plaques. These features exist before the clinical diagnosis is made (Knopman et al., 2003). Studies have documented lexical-semantic impairments in people with AD (Albert et al., 2011; Rogers & Friedman, 2008), and semantic errors have been associated with deficits in processing speed and lexical retrieval (Moreaud et al., 2001). Degradation of the structure and organization of semantic memory (Moss et al., 1995) has also been reported, that is, a loss of the stored knowledge of words and their relationships with other words and concepts, events, and objects (Martínez-Nicolás et al., 2019). Semantic memory has been studied on a behavioral level mainly using verbal fluency, naming, and lexical decision tasks. Implicit tasks, such as those based on priming, have been used less often. Verbal fluency and naming tasks rely on production: an explicit response. People with AD score lower than older adults with typical aging (TA) on categorical verbal fluency tasks, which measure the production of words that name referents of the same category, such as "animals" (Hodges et al., 1996), and on naming tasks (Chertkow & Bub, 1990). Categorical verbal fluency tasks require participants to find and organize their responses, remembering and inhibiting their previous responses to avoid repetition. Naming tasks have been used to monitor the increase in non-response errors as the disease progresses. Priming tasks, however, rely on comprehension: they implicitly reveal the organization of a semantic network. The priming effect, which produces a faster or more accurate response in processing a target word when it is preceded by a related word (a prime) than when it is preceded by an unrelated word (Meyer & Schvaneveldt, 1971), can be used to explore the semantic and lexical levels of language processing (Dell, 1986; McClelland & Elman, 1986). Semantic priming is a rapid and automatic process; it does not require strategic processes, minimizing the influence of non-semantic cognitive factors (Neely, 1991).

Some researchers have explained lexical-semantic problems in people with AD as a failure to retrieve information, slowing the process of finding words and causing errors, due to impairments in the executive and attentional processes involved (Rohrer et al., 1995). Others have described these problems as a degradation of stored knowledge that impairs the organization and structure of the semantic network (Haugrud et al., 2011). Duong et al. (2006) have proposed the existence of impaired access to the semantic system in people with mild cognitive impairment (MCI) prior to conversion to AD. Salehi et al. (2017) have also proposed that in the early stages of AD, retrieval causes difficulties in producing an adequate semantic network, followed later by degradation of the system.

Cimminella et al. (2021) evaluated the semantic interference in extrafoveal vision in people with AD and a control group. Participants were shown an array of five images: one target (e.g., "car") and four related distractors (e.g., vehicles) or four unrelated distractors (e.g., kitchen utensils). The results showed that both the AD and the control group had greater detection difficulties in the related than in the unrelated conditions, but the difference was greater in the AD group. The authors

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concluded that semantic processing was preserved in people with AD but that they had problems with accessing the semantic information. In contrast, Guglielmi et al. (2020) have reported degradation from the early stages of the disease, finding that the group converting from MCI to AD did not show a priming effect. These results suggest an early impairment in semantic relationships rather than a deficit in the accessibility of semantic stores in people who convert to AD.

Semantic storage, which encompasses meaning, is inherently multidimensional. It includes representations associated with the meaning of words, in dimensions such as taxonomic categories, functional attributes, associative relationships, and thematic connections, allowing for a rich and flexible understanding of language. By presenting a priming task that measures visual preference to a named target preceded by a prime that is related thematically, taxonomically, or both, this study aims to measure the degree of semantic impairment in people with moderate AD.

In thematic links, word pairs appear together in the same scenario or event; they refer to causal, functional, spatial, and temporal relationships (Estes et al., 2011; Lin & Murphy, 2001), such as "milk"–"cow" or "key"–"door." Although pairs can be based solely on word co-occurrence, such as "iceberg"–"lettuce" or "eggs"–"bacon," there is evidence that such pairs are insufficient to produce priming effects, as they are considered merely lexical, not semantic (Yee et al., 2009). In taxonomic links, the referents of the words belong to the same semantic category (e.g., "animals," as in "dog"–"cow"). Taxonomic relationships are based on shared features, such as being mammals, edibles, or musical instruments (Estes et al., 2011; Rosch, 1975). In combined links (e.g., "dog"–"cat"), both words belong to the same semantic category, and it is also common to find them in the same context (Hutchison et al., 2008).

Different responses have been found in people with AD and TA with thematic versus taxonomic links. Sass et al. (2009) found a significant priming effect in people with TA for thematic pairs but not for taxonomic ones. Simoes Loureiro and Lefebvre (2016) also found a greater impairment with taxonomic than with thematic links and greater impairment with natural objects (e.g., animals, fruits) than with manufactured objects (e.g., tools, vehicles). However, Merck et al. (2023) found a general reduction, in comparison to young adults, in sensitivity to semantic competitors, both for taxonomic and thematic relationships in people with TA.

Taxonomic and thematic relationships seem to involve different neuroanatomical areas. Taxonomic links deteriorate first: they activate bilateral visual areas in the anterior temporal lobe, while thematic ones rely more on the temporoparietal cortex, which is also involved in action, motion, and spatial processing (Kalénine et al., 2009; Kalénine & Buxbaum, 2016; Sachs et al., 2011; Zhang et al., 2023; but see Peelen & Caramazza, 2012, for divergent patterns). Another hypothesis, the "hub and spoke" model of semantic memory (Patterson et al., 2007), describes a single system led by the anterior temporal lobe, which processes both types of relationships. A temporal distinction has also been found for thematic and functional relationships in semantic eye-tracking tasks (visual selection of an object that matches a target) in healthy older people (Kalénine et al., 2012) and stroke patients (Kalénine & Buxbaum, 2016). Kalénine et al. (2012) found that participants fixated earlier on thematically related items (e.g., "broom"–"dustpan") than general functional relationships (e.g., "broom"–"sponge") or specific functional ones (e.g., "broom"–"vacuum cleaner"). In a study using event-related potentials, Wamain et al. (2015) also found earlier activation for thematic

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relationships (e.g., "saw"–"wood") than for functional ones (e.g., "saw"–"knife") in people with TA.

Studies of people with AD performing semantic priming tasks have shown a deterioration of the semantic system as the disease progresses in distinguishing between taxonomic pairs. For example, Giffard et al. (2002) reported that people in the initial stages of AD displayed a hyperpriming response (an increased or exaggerated priming effect) for taxonomic relationships, as if they were exposed to a repetition, where "cat" and "dog," for example, were almost treated as synonyms (Giffard et al., 2002; Perri et al., 2011). As the disease progressed, a hypopriming response (a lower-than-normal priming effect) was found when the target was an attribute of the prime, as in "stripes"–"tiger" (Giffard et al., 2002). This result was consistent with Rogers and Friedman's (2008) finding of a reduced priming effect with category coordinates, reflecting a lack of facilitation from the prime to the target in pairs like "cat"–"dog." Giffard et al. (2001) and Giffard et al. (2002) argue that the loss of distinctive features in the early stages of AD (e.g., stripes for "tiger" vs. "lion") causes a degradation of semantic memory. Laisney et al. (2011) found a hyperpriming effect with coordinates, irrespective of their semantic distance (e.g., "tiger"–"lion" vs. "tiger"–"elephant") and agrees with Giffard et al. (2001) and Giffard et al. (2002) that the hyperpriming effect reflects a loss of distinctive features between concepts in people with AD.

The results of these studies are influenced by the characteristics of the samples, the stage of the disease, and the methods used and also by the type of relationship between the pairs of words. Perri et al. (2019) performed a detailed exploration of the causes underlying problems in semantic priming in people with AD and a control group, finding that the dominance (characteristics of a concept frequently elicited) of the target predicted the priming effect in people with AD: less dominant targets presented lesser effects. These results indicate that attributes of semantic memory, such as a high level of feature dominance, are more resistant to memory degradation. Perri et al. (2019) also suggest that thematic relationships formed with a high level of feature dominance (e.g., "elephant"–"trunk") are more resistant to memory degradation in people with AD.

Theoretical models describe vocabulary as structured in semantic memory (Tulving, 1972, 1983), organized in a network where word representations are the nodes and relationships between representations are links (Anderson, 1983; Collins & Loftus, 1975; Dell, 1986; McClelland & Elman, 1986). Different models have proposed distinct mechanisms of transmission of information in semantic memory. Spreading-activation models describe activation spreading between related concepts, facilitating lexical access to coactivated concepts (Collins & Loftus, 1975). In these models, the links between related concepts are created by the concurrence of words in speech or referents in the environment, using a Hebbian-like rule. Distributed network models, including the proximity model, describe primes and targets that are close to each other in a high-dimensional semantic space; the coactivation between semantically related concepts is thus a consequence of overlapping patterns of activity (McNamara, 2005). The damage in taxonomic relationships suggests a difficulty in processing similarity in features resulting from a deteriorated distribution in the network and a lack of activation from a node to a related node. According to the proximity model, the preservation of thematic links

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would indicate that words are activated because they share a context or co-occur in lexical space. However, it is not known whether simultaneous taxonomic and thematic relationships would emphasize the relationship or damage the link, as shared features and context can saturate the semantic systems of people with AD.

Current study

This study used participants' visual preferences for a target picture, after hearing a target word preceded immediately by a related or unrelated prime word, to determine the presence or absence of a priming effect tapping into word-word links. It also used these preferences to evaluate the deterioration of purely thematic and purely taxonomic links in the moderate stage of AD. We expected that as in previous studies, the degradation of the semantic store for people with AD would be seen with taxonomically related pairs (e.g., "ship"–"airplane"), but not with thematically related pairs (e.g., "key"–"door"). In addition, we evaluated whether having two simultaneous thematic and taxonomic relationships enhanced the priming effect. The priming boost effect, previously demonstrated with adults, produces a strong priming effect with words that have two kinds of relationships, as the pairs of words share both features and spatial or temporal context. It is thus possible that the taxonomic deterioration would be overcome by the strong effect of two types of relationships. However, it is also possible that excessive sources of semantic overlapping would saturate semantic memory processing, resulting in no priming effect. Adding a type of relationship could degrade the semantic system or create a competition effect in which the priming effect of thematic pairs disappears because of interference on the taxonomic level. We hypothesized that participants with TA would exhibit a priming effect regardless of the type of relationship.

Participants viewed two images, one of whose name was also heard, preceded by a semantically related or unrelated auditory prime. If there is a priming effect, the presentation of a related or unrelated word would influence target identification (McMurray, 2023). The presentation of an unrelated target typically causes interference in target identification regardless of age (Angulo-Chavira & Arias-Trejo, 2018, 2021; Arias-Trejo et al., 2022; Arias-Trejo & Plunkett, 2013; Mani & Plunkett, 2011). Consequently, we expected to observe semantic interference in unrelated trials with the TA group as a demonstration of the priming effect. We expected this effect to be present in the AD group only in the thematic condition.

Method

Participants

Table 1 shows the demographic and neuropsychological characteristics of the participants. The criteria for inclusion were to be right-handed, adults, native speakers of Spanish, and with test scores defined for the AD and TA groups. Participants were excluded if they were diagnosed with another neurological or psychiatric illness or used stimulant or depressant drugs unrelated to AD treatment. The sample analyzed consisted of 16 patients with AD (8 women), with a mean age of 73.69 years ($SD = 11.55$), and 16 healthy adults with TA (12 women), with a mean age of 74.75 years ($SD = 9.33$). Seven people with AD were excluded from the

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Table 1. Characteristics of TA and AD groups

Variable	Measure	TA	AD	Statistic
Sex	Male	4	8	$p = .273^{+}$
	Female	12	8	
Age (years)	*M*	74.75	73.69	$t(31) = 0.286$
	SD	9.33	11.55	$p = .777$
Education (years)	*M*	10.94	7.63	$t(31) = 1.712$
	SD	5.45	5.50	$p = .097$
MMSE	*M*	**27.25**	**14.75**	$\mathbf{t(31) = 6.619}$
	SD	**2.54**	**7.11**	$\mathbf{p < .001}$
GDS	*M*	1.63	2.50	$t(31) = 1.464$
	SD	1.50	1.86	$p = .154$
Katz	*M*	**0.19**	**1.00**	$\mathbf{t(31) = 2.448}$
	SD	**0.40**	**1.26**	$\mathbf{p = 0.024}$

Notes: Bold values are statistically significant comparisons. TA: typical Aging; AD: Alzheimer's disease; MMSE: Mini-Mental State Examination; GDS: Geriatric Depression Scale; Katz: Katz Index of Independence in Activities of Daily Living. [+]Comparison using Fisher's test.

analysis because they did not meet the inclusion criteria. Of these, four had neurological and/or psychiatric comorbidities, two had calibration problems, and one did not pay attention to the task. Thirteen participants with TA were excluded: five with cognitive impairments according to the Mini-Mental State Examination (MMSE) and thus a failure to meet the inclusion criteria and eight because they could not be matched with an AD patient. Participants with AD were recruited at the Manuel Velasco Suárez National Institute of Neurology and Neurosurgery (INNN-MVS). They were diagnosed with dementia by a clinical professional, supported by neuroimaging studies and the DSM-5 criteria for major cognitive disorders due to AD (American Psychiatric Association, 2013). Those with TA were recruited at senior education centers. All procedures performed in this study were approved by the Research Ethics Committee of the INNN-MVS (Protocol No. 40/18, "El rastreo visual como un instrumento de medición de relaciones léxicas en pacientes con trastorno neurocognitivo mayor"). All non-excluded participants were evaluated in all three experiments.

Participants were evaluated using (1) the MMSE (Folstein et al., 1975) to measure the existence of cognitive impairment; participants with AD were included if they scored less than 24 points, indicating cognitive impairment, and those with TA if they scored more than 27 points, indicating normal cognitive functioning; (2) the Geriatric Depression Scale (GDS-15) (Yesavage & Sheikh, 1986) to rule out depression symptoms; participants in both groups were excluded if they scored more than 5 points, indicating the presence of symptoms of depression; and (3) the Katz Index of Independence in Activities of Daily Living (Katz et al., 1963) to corroborate their functional status; patients with AD were included irrespective of their functionality,

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but those with TA were included if they scored less than 1, indicating full functioning. Although the TA and AD groups had different proportions of women and men, the Fisher test showed no difference between them ($p = .273$). Independent t-tests displayed no statistically significant differences between groups regarding age, schooling, or depression, according to the GDS-15. As expected, the moderate AD group presented lower cognitive performance according to the MMSE and lesser functioning in daily life activities than the TA group (Table 1).

Stimuli

General stimuli

Ninety concrete and familiar nouns were used, 30 nouns per experiment (10 primes, 10 targets, and 10 distractors). All were words of early acquisition, according to the MacArthur-Bates Communicative Development Inventories (Jackson-Maldonado et al., 2003). Words of early acquisition were selected to maximize the chances of obtaining a priming effect: previous studies have found that people with AD produce words that are frequent, typical, and of early acquisition, so words acquired early are likely to produce such effects (Sailor et al., 2011; Vita et al., 2014). The prime words were presented orally, and the target and distractor were pictures presented on a screen. The three experiments included two conditions, according to the type of prime-target relationship: related or unrelated.

Audio stimuli

A female native speaker of Spanish digitally recorded the auditory primes and targets in a soundproof room. The recordings were edited at 44,100 Hz and 32 bits. The audios were normalized using Adobe Audition software and adjusted in amplitude and volume. A total of 60 audio stimuli were obtained, 10 per experiment.

Visual stimuli

Sixty visual stimuli were selected from Snodgrass and Vanderwart's (1980) database, with degree of complexity, concordance, familiarity, and denomination as validation criteria, to make up 30 target-distractor pairs of prototypical images of concrete and familiar nouns. All images were black-and-white drawings of the same size to ensure similarity between target and distractor. Visual stimuli were presented on a 1440 × 1080-pixel gray background (RGB: 255, 255, 255). Target images appeared on the left-hand side of the screen in half of the trials and on the right-hand side in the other half.

Experimental task

We used eye tracking as a method to study lexical-semantic organization in an implicit manner to reduce the top-down effect. The eye-tracking paradigm is a noninvasive method that taps into a reserve capacity in people with AD to respond to implicit cues (Crawford et al., 2015). Pictures in an implicit task are easier for people with AD to process than written words because the perceptual system supports the semantic representation (Cimminella et al., 2021). The use of an eye tracker, requiring only looking at images as words are heard, reduces the effect of slower cognitive processing in the elderly (Salthouse, 1996) and other impaired

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populations, minimizing the influence of the attentional and executive processes. This method guarantees the automaticity of rapid priming effects and avoids the influence of strategic processes.

Experiment 1: taxonomic-thematic priming

In the combined taxonomic-thematic experiment, prime and target had a double link: they belonged to the same superordinate category and contextual co-occurrence (Table 2). For example, "dog" and "cat" are both animals, and they often occur together (e.g., in a home). Contextual co-occurrence was verified using the percentage of associative strength from the Word Association Norms Database for Mexican Spanish (Arias-Trejo & Barrón Martínez, 2014). In the three experiments, the prime, target, and distractor words were phonologically unrelated in onset and rhyme to avoid phonological priming effects (Angulo-Chavira & Arias-Trejo, 2018; Mani & Plunkett, 2011), and the target and distractor words had the same grammatical gender in Spanish to avoid morphological priming (Bobb & Mani, 2013).

Experiment 2: taxonomic priming

In the taxonomic experiment, prime and target belonged to the same semantic category and lacked contextual co-occurrence (Table 3). The absence of contextual co-occurrence was ascertained from the Word Association Norms Database for Mexican Spanish (Arias-Trejo & Barrón-Martínez, 2014), following the criterion that the prime and the target had an associative strength of less than 0.33%. Words were phonologically and thematically unrelated.

Experiment 3: thematic priming

In the thematic experiment, prime and target had contextual co-occurrence and belonged to a different superordinate category (Table 4). To determine contextual co-occurrence, a high percentage of associative strength was verified using the Word Association Norms Database for Mexican Spanish (Arias-Trejo & Barrón-Martínez, 2014). Words were phonologically and taxonomically unrelated.

Procedure

Caregivers of the participants with AD signed an informed consent form and filled out a sociodemographic questionnaire asking about their age, sex, diagnosis, date of diagnosis, illnesses, and treatments. TA participants signed the consent form and filled out the questionnaire themselves. Each participant was evaluated in a single session of approximately an hour. The order of presentation was pseudorandomized as follows: (1) an experimental priming task, (2) the MMSE, (3) a second experimental task, (4) the GDS-15, (5) a third experimental task, and (6) the Katz Index of Independence in Activities of Daily Living. The evaluations were carried out in two cubicles: one to perform the experiments and the other for the neuropsychological assessments.

A Tobii X2-30 portable eye tracker was used to present the task in participants' healthcare facilities or nursing homes to avoid a laboratory setting where they might

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Table 2. Primes, targets, and distractors used in the taxonomic-thematic experiment

Taxonomic-thematic related condition					Taxonomic-thematic unrelated condition				
Prime	Target	Distractor	% Association prime-target	% Association target-prime	Prime	Target	Distractor	% Association prime-target	% Association target-prime
cuchara (spoon)	tenedor (fork)	pájaro (bird)	15.56	13.09	árbol (tree)	dedo (finger)	reloj (clock)	0	0
sol (sun)	luna (moon)	caja (box)	19.20	24.09	casa (house)	payaso (clown)	pescado (fish)	0	0
tigre (tiger)	león (lion)	dulce (candy)	11.25	7.59	hormiga (ant)	escalera (stairs)	bicicleta (bicycle)	–	0
gato (cat)	perro (dog)	mango (mango)	37.22	27.06	estrella (star)	collar (necklace)	chile (chili pepper)	0	0
mesa (table)	silla (chair)	bota (boot)	23.17	19.14	pastel (cake)	caballo (horse)	sombrero (hat)	0	0

Note: The missing value indicates that the stimulus was not included in the database.

Table 3. Primes, targets, and distractors used in the purely taxonomic experiment

Taxonomic related condition					Taxonomic unrelated condition				
Prime	Target	Distractor	% Association prime-target	% Association target-prime	Prime	Target	Distractor	% Association prime-target	% Association target-prime
pierna (leg)	boca (mouth)	vela (candle)	–	0	cobija (blanket)	jugo (juice)	libro (book)	0	0
brazo (arm)	nariz (nose)	tina (tub)	0	–	martillo (hammer)	galleta (cookie)	ventana (window)	0	0
burro (donkey)	oso (bear)	tambor (drum)	0.33	0	ropero (wardrobe)	naranja (orange)	tortuga (turtle)	–	0
barco (ship)	avión (airplane)	helado (ice cream)	0	0	carro (car)	manzana (apple)	oreja (ear)	–	–
zapato (shoe)	pantalón (trousers)	cuchillo (knife)	0.33	1.45	espejo (mirror)	lápiz (pencil)	cerdo (pig)	0	0

Note: Missing values indicate that the stimulus was not included in the database.

feel uncomfortable. In the experimental sessions, the participants were seated 60 cm from an LED monitor (23-inch, resolution 1920 × 1080). The eye tracker was employed to record participant gaze; this device records and analyzes eye movements using infrared diodes with a sampling rate of 30 Hz. Each participant received individual instructions prior to calibration, which stated: "Please focus on the images and sounds that will appear on the screen. During the presentation, remain seated, and avoid moving your head or arms, or speaking." Before each experiment, participants performed a five-point calibration by looking at images at the center and in each of the four corners of the screen. The calibration was considered acceptable when their gaze was tracked correctly for at least three of the five images for each eye. If the calibration was not acceptable on the first attempt, it was repeated a maximum of two additional times. After calibration was completed, the following instructions were given: "Please continue focusing on the images and sounds on the screen and avoid moving or speaking. Remember, this is not a test; we are simply interested in observing your visual preferences for a few minutes."

Five related and five unrelated trials were presented in each experiment in a pseudorandomized order (no more than two trials from the same condition were presented consecutively). Each trial had a duration of 3600 ms (Figure 1). At the beginning of the trial, participants were presented with an attention-getter (0–1100 ms), followed by the target and distractor pictures for 2500 ms (1100–3600 ms). The onset of the prime word varied, but the word always ended at 700 ms, and the onset of the target word was presented at 900 ms. Thus, the inter-stimulus interval and the stimulus-onset asynchrony between prime and target lasted 200 ms.

The three experiments were organized in two sequences: taxonomic-thematic-combined (A-B-C) and thematic-taxonomic-combined (B-A-C), with the combined experiment always presented last because it involved the two levels first presented in isolation. In both sequences, a two-minute pause occurred between the first two experiments to allow the participant to adjust or perform relaxation movements. Before moving on to Experiment 3, a 10-minute break was provided, during which participants could take a walk, use the restroom, or complete any remaining tests from the evaluation protocol. Since the target position could be on the right (R) or left (L) side of the screen, the experiment sequences were mixed with these target positions, resulting in four different sequences (AR, BR, CR; AL, BL, CL; BR, AR, CR; BL, AL, CL). These four sequences were randomly assigned to participants, with control measures in place to ensure counterbalanced presentation across participants.

Data analysis

To analyze gaze data, two areas of interest were defined with target and distractor images of identical size and location. The fixations to the target were measured in a time window from 0 to 2500 ms relative to the image onset (see Figure 1). Blinks and fixations outside the screen were considered missing data. Trials where participants did not look at the screen for at least 50% of the time were excluded from the final analysis. However, most participants completed all trials, indicating that attention was maintained in people with AD (taxonomic-thematic: $M = 9.56$ trials, $SD = 0.51$; thematic: $M = 9.73$ trials, $SD = 0.45$; taxonomic: $M = 10$ trials, $SD = 0$) and in those with TA (taxonomic-thematic: $M = 9.43$ trials, $SD = 0.51$;

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Table 4. Primes, targets, and distractors used in the purely thematic experiment

Thematic related condition					Thematic unrelated condition				
Prime	Target	Distractor	% Association prime-target	% Association target-prime	Prime	Target	Distractor	% Association prime-target	% Association target-prime
juguete (toy)	niño (boy)	botón (button)	38.54	4.01	flor (flower)	queso (cheese)	jabón (soap)	0	0
huevo (egg)	gallina (hen)	muñeca (doll)	32.36	31.27	radio (radio)	pelota (ball)	sandía (watermelon)	0	0
cuna (crib)	bebé (baby)	pato (duck)	70.96	.37	calcetín (sock)	pan (bread)	tren (train)	0	0
llave (key)	puerta (door)	gorra (cap)	49.09	.33	toalla (towel)	plato (plate)	globo (balloon)	0	0
leche (milk)	vaca (cow)	falda (skirt)	24.08	52.36	tambor (drum)	abeja (bee)	escoba (broom)	0	0

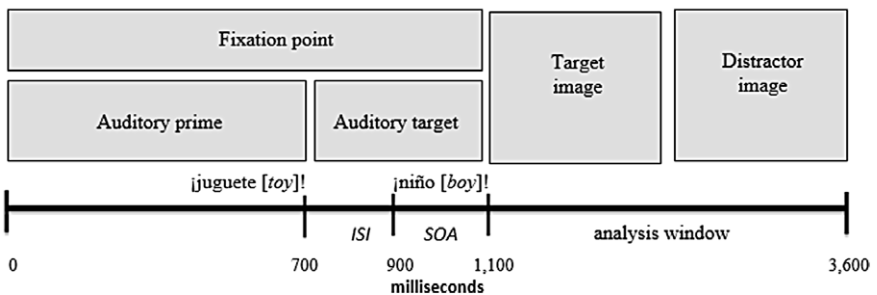

Figure 1. Example of a thematic related sequence.

thematic: $M = 9.68$ trials, $SD = 0.47$; taxonomic: $M = 10$ trials, $SD = 0$). Eye-tracking data were analyzed separately for each experiment using a logistic mixed-effect model with the *glmmPQL* function of the *Mass* package in R (R Core Team, 2019). To improve model convergences and fitting, all categorical variables were contrast coded as follows: Group (TA = –0.5, AD = 0.5) and Condition (related = –0.5, unrelated = 0.5).

We used a complex model that made sense for our theoretical questions and methodological design (Barr, 2008). The models for the three experiments included the fixed factors Group (TA, AD) and Condition (Related, Unrelated). For the random structure, we used the slope of Condition over Subject, with the intercept Items. The slope of Condition over the random factor Item was not included because participants were tested in a between-items design (Barr, 2008) where different words were presented for Related and Unrelated conditions. Similarly, Group is a between-subject factor, so it was excluded from the random structure (Barr, 2008). Planned follow-up paired comparisons explored the Related versus Unrelated contrast and were performed with the function *emmeans*.

Given the considerable variability in MMSE scores within our AD group, we employed a logistic model to explore whether cognitive impairment influenced the priming effect. This model was similar to the one previously described, but it focused exclusively on the AD group and its interaction with MMSE scores as a fixed factor. The random structure produced similar results as in the previous analysis.

Results

Experiment 1: thematic-taxonomic priming

In the logistic mixed-effect model, the proportion of target looking (PTL) was not significantly predicted by the main factor Group or Condition (p-values $> .17$); however, the interaction between Group and Condition was a significant predictor ($p = .035$). Follow-up analyses showed that the TA group, $\beta = 0.47$, $SE = 0.27$, $t(246) = 1.69$, $p = .09$, but not the AD group, $\beta = -0.25$, $SE = 0.23$, $t(246) = -1.08$, $p = .28$, had a marginally significant difference between Related (TA: $M = .59$, $SD = 0.19$; AD: $M = .49$, $SD = 0.18$) and Unrelated (TA: $M = .44$, $SD = 0.25$; AD: $M = .54$, $SD = 0.17$) conditions (Table 5; Figure 2). This result suggests that participants with TA exhibited a priming effect with thematic-taxonomic pairs of words, whereas those with AD did not. However, it is important to note that the paired comparisons were only marginally significant. There was no significant influence of MMSE scores on the priming effect, $\beta = 0.02$, $SE = 0.02$, $t(128) = 1.12$, $p = .26$.

Experiment 2: taxonomic priming

The logistic mixed-effects model revealed that the PTL was not significantly predicted by the main factor Group ($p = .90$); however, the main factor Condition ($p = .01$) and the interaction between Group and Condition were significant predictors ($p = .06$). Note that our main interaction was marginally significant, but we performed the interaction in the follow-up analysis based on our theoretical

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Table 5. Statistics of the linear mixed-effect model for the thematic-taxonomic experiment

Fixed effects	*β*	*SE*	*df*	*t*	*p*
Intercept	0.155	0.109	9810	1.418	0.156
Condition	−0.034	0.218	246	−0.157	0.875
Group	−0.305	0.218	30	−1.396	0.172
Condition: Group	**0.927**	**0.437**	**246**	**2.12**	**0.035**

Note: Bold values represent significant main effects or interactions. Formula: PTL ~ Condition * Group + (Condition | Subject) + (1| Item).

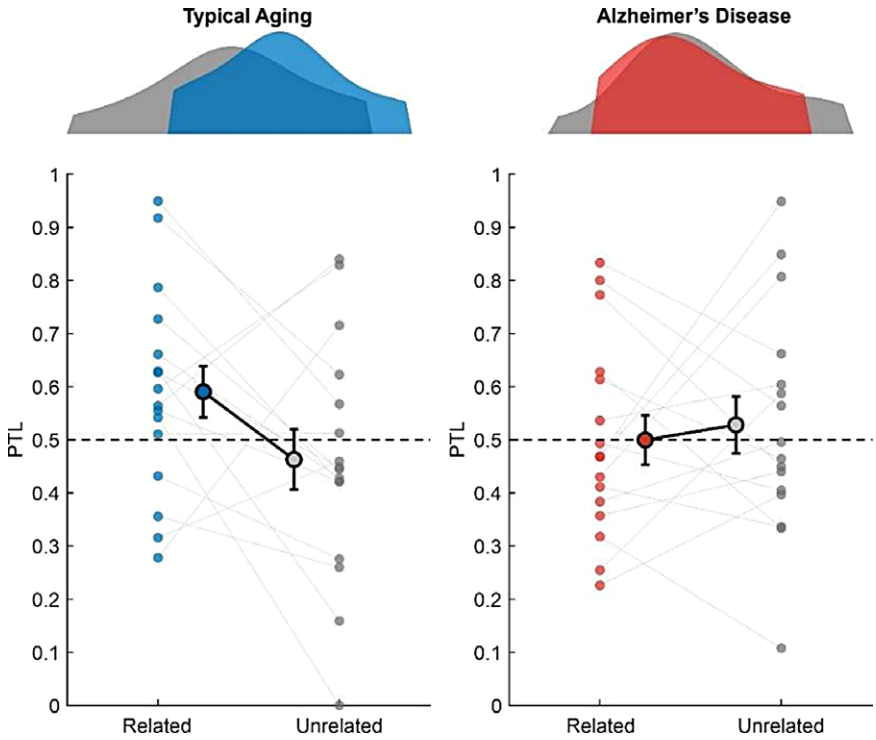

Figure 2. Results of Experiment 1: Thematic-taxonomic priming. *Note*. Density plots represent the marginal distributions of the average of fixations to the target (PTL). Red and blue dots represent the individual PTL in the Related condition, and gray dots represent the PTL in the Unrelated condition. Error bars indicate the mean and ±1 standard error.

questions. Follow-up analyses showed that the TA group, $\beta = 0.74$, $SE = 0.24$, $t(269) = 3.041$, $p = .002$, but not the AD group, $\beta = 0.10$, $SE = 0.24$, $t(269) = 0.422$, $p = .67$, had higher PTL in the Related (TA: $M = .60$, $SD = 0.17$; AD: $M = .56$, $SD = 0.17$) than in the Unrelated (TA: $M = .45$, $SD = 0.20$; AD: $M = .51$, $SD = 0.17$) condition (Table 6; Figure 3). Thus, participants with TA, but not those with AD, presented a priming effect with taxonomic pairs of words. This interpretation should be approached with caution, as it

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Table 6. Statistics of the linear mixed-effect model for the taxonomic experiment

Fixed effects	β	*SE*	*df*	*t*	*p*
Intercept	**0.251**	**0.085**	**10694**	**2.939**	**0.003**
Condition	**–0.422**	**0.171**	**269**	**–2.466**	**0.014**
Group	0.02	0.171	30	0.12	0.905
Condition: Group	**0.641**	**0.342**	**269**	**1.875**	**0.061**

Note: Bold values represent significant main effects or interactions. Formula: PTL ~ Condition * Group + (Condition | Subject) + (1| Item).

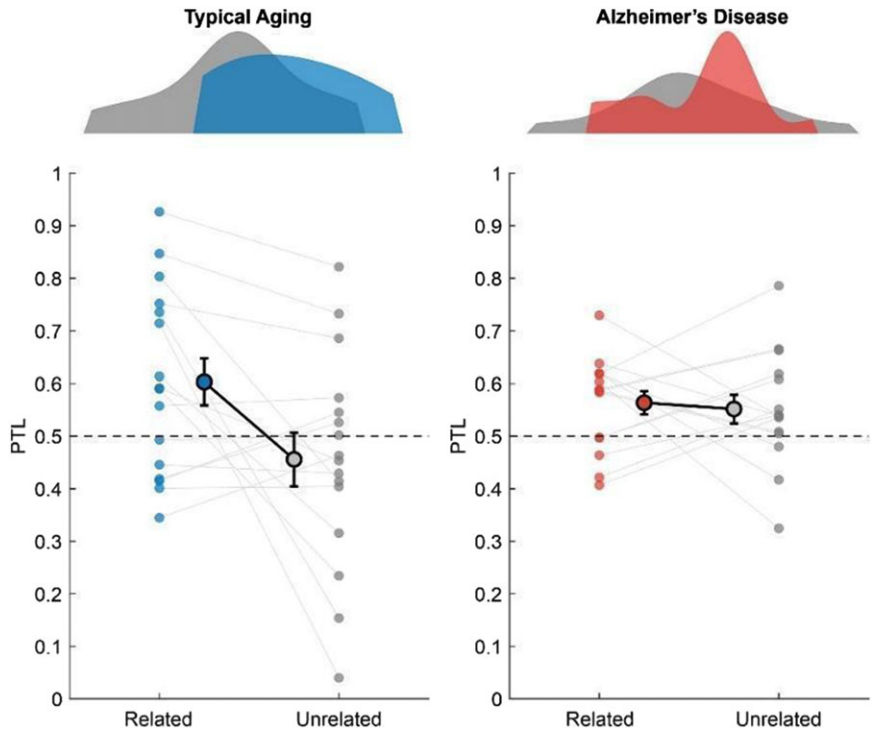

Figure 3. Results of Experiment 2: Taxonomic priming. *Note*. Density plots represent the marginal distributions of the average of fixations to the target (PTL). Red and blue dots represent the individual PTL in the Related condition, and gray dots represent the PTL in the Unrelated condition. Error bars indicate the mean and ±1 standard error.

is based on a marginal statistical result. There was no significant influence of MMSE scores on the priming effect, $\beta = -0.004$, $SE = 0.01$, $t(135) = 0.37$, $p = .71$.

Experiment 3: thematic priming

The logistic mixed-effect model revealed that the PTL was significantly predicted by condition ($p = .005$) with participants of both groups looking more in the Related

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Table 7. Statistics of the linear mixed-effect model for the thematic experiment

Fixed effects	*β*	*SE*	*df*	*t*	*p*
Intercept	0.129	0.112	9845	1.145	0.252
Condition	**–0.632**	**0.225**	**253**	**–2.798**	**0.005**
Group	–0.193	0.225	29	–0.856	0.399
Condition: Group	0.12	0.451	253	0.266	0.79

Note: Bold values represent significant main effects or interactions. Formula: PTL ~ Condition * Group + (Condition | Subject) + (1| Item).

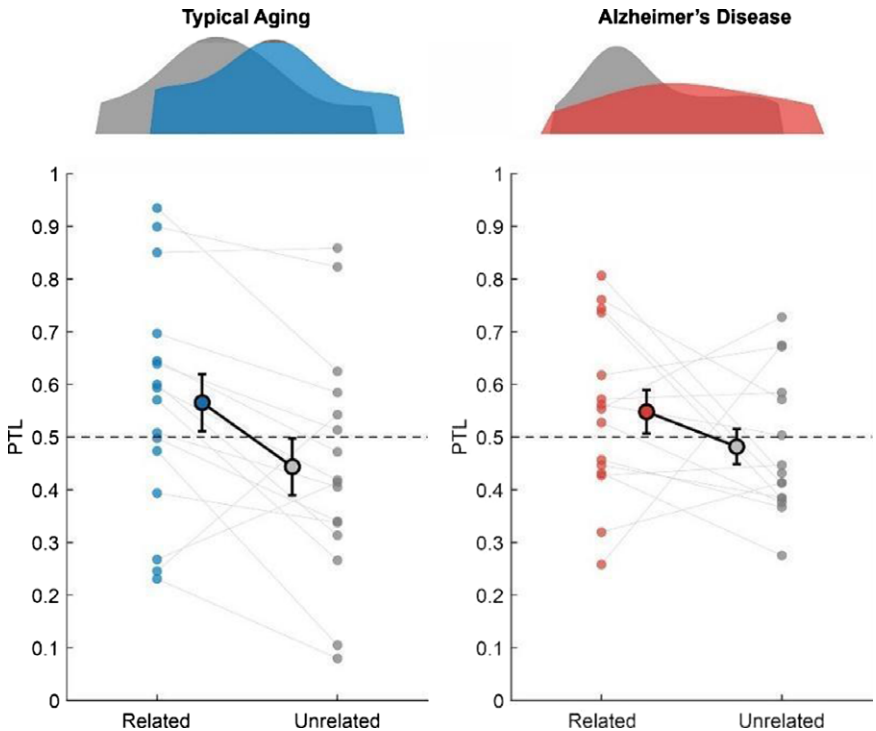

Figure 4. Results of Experiment 3: Thematic priming. *Note*. Density plots represent the marginal distributions of the average of fixations to the target (PTL). Red and blue dots represent the individual PTL in the Related condition, and gray dots represent the PTL in the Unrelated condition. Error bars indicate the mean and ±1 standard error.

($M = .55$, $SD = 0.19$) than in the Unrelated trials ($M = .46$, $SD = 0.17$); however, neither the Group main effect nor the interaction between Group and Condition was a significant predictor (Table 7; Figure 4). This result indicated that both the TA and AD groups presented a priming effect with thematic pairs of words. There was no significant influence of MMSE scores on the priming effect, $\beta = -0.02$, $SE = 0.02$, $t(126) = 1.11$, $p = .26$.

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Discussion

This study explored semantic memory in patients with AD and a control group with typical TA. Using an eye tracker, it evaluated whether combined taxonomic-thematic, purely taxonomic, and purely thematic relationships produced a priming effect. In Experiment 1, with combined taxonomic and thematic relationships, participants with TA, but not those with AD, presented a priming effect, supporting the hypothesis that simultaneous shared features and context would saturate the semantic systems of people with AD. In Experiments 2 and 3, our hypotheses were confirmed: participants with AD showed priming effects with purely thematic relationships but not with purely taxonomic ones, and participants with TA showed priming effects in both experiments. Moreover, the unrelated prime seems to have an interference effect, as target looking was at chance level.

The TA group presented a priming effect in all three experiments that reflected a preserved connection between words, presenting either a combination of relationships or a pure relationship. However, this group did not benefit from the semantic boost reported with adults, that is, a greater priming effect for pairs of words linked at two levels (Experiment 1) rather than at one (McRae & Boisvert, 1998; Moss et al, 1995; Lupker et al., 2022). This result could reflect the loss in older adulthood of this benefit of the relationship between words. It is also possible that the slower response times of people with TA (Salthouse, 1996) hide this boosting effect: the effect may exist even if it was not captured by the study design.

This lack of a priming effect with combined thematic-taxonomic relationships in people with AD, and with purely taxonomic links (Experiment 2), is compatible with the findings of Guglielmi et al. (2020) and Simoes Loureiro and Lefebvre (2016), who describe a progressive deterioration of the semantic system, particularly with purely taxonomic relationships (but see Merck et al., 2019, who found no difference between the relationships in people with AD). This outcome is consistent with the spreading-activation model: there is an absence of activation from the prime to the target word in the taxonomic condition, where two words are presented from the same category but without associative strength. However, there is also interference when thematic and taxonomic relationships are presented simultaneously, which is consistent with diffuse network models (including also proximity models; see Collins & Loftus, 1975); the short distance between nodes (concepts) is diffuse and perhaps overlapping (and no longer distinguishable). The activation is diffused, as the prime node either spreads activation in all directions or cannot spread activation to a particular direction (in Experiment 1, combined links may freeze the process). This implies that concepts are not connected, as they are further away than unrelated ones, and retrieval is affected. The lack of a priming effect in the combined links could therefore also relate to a saturation of information, where there are too many traits to process simultaneously. The relationships compete, causing saturation in the semantic system of people with AD as they process both features and context at the same time; the combination of shared and distinctive categorical features and proximity in context, space, or function overloads a deteriorated semantic system. With the progression of the disease, the connection between semantic links could be compromised, hindering taxonomic-thematic relationships.

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Only one lexical decision task presenting written words (Glosser & Friedman, 1991) has found combined taxonomic-thematic priming (with high-frequency words that are also highly associated, e.g., "sheep"–"goat") in people with AD, although it also found impairment with purely taxonomic pairs. It is possible that in our experiment, the mixed presentation of auditory (prime-target) and visual (target-distractor) stimuli taxed the semantic system. This double processing route can produce an inhibitory effect on the lexical level when a taxonomic referent is processed. While the target picture is first processed at the semantic level and its lexical representation is then recovered, the auditory prime is first processed at the lexical level and its meaning then recovered (Huettig & Altmann, 2007). However, as in Glosser and Friedman (1991), reading may be challenging for people with AD when they are asked to decide whether a string of letters is a word. Although MMSE scores did not predict any change in priming effects, the influence of education on the speed of degradation of the semantic system remains to be explored.

We did not see an effect for purely taxonomic word pairs in Experiment 2. Some researchers (e.g., Grasso & Saux, 2020) have attributed the decline of semantic memory in people with AD to the progressive loss of the connection between features or attributes underlying the representation of the semantic categories in lexical networks, thus delaying their ability to discriminate between concepts that belong to the same category. This loss of connection could affect the semantic processing level, reducing the priming effect of taxonomically related words. In fact, some studies have suggested that a neuropathological difference between TA and AD is that explicit memory (declarative) problems can be experienced in the former, while in the latter, these deficits are accompanied by an impairment in category-exemplar priming (Fleischman et al., 2005).

In contrast to some studies (Laisney et al., 2011; Perri et al., 2011), we did not find hyperpriming for taxonomic pairs. This result may be a consequence of using pairs that did not share associative strength, where each element could still be treated as dissimilar ("shoes"–"pants"), as opposed to pairs like "lion"–"tiger" (Perri et al., 2011), that share features such as being furry, being felines, and living in the jungle, which people with AD might treat as identical. In addition, Giffard et al. (2001) and Giffard et al. (2002) argue that distinctive traits may be lost in the early stages of AD. Giffard et al. (2002) and Laisney et al. (2011) argue that hyperpriming is transient: they found that people in the early stages of the disease showed this phenomenon. Since our participants were in the moderate stage of the disease, they may already have passed this phase and therefore demonstrated the lack of a hyperpriming effect. We captured a semantic deterioration process at the moderate stage of AD, suggesting a bottom-up deterioration of semantic memory caused by specific attributes for taxonomic pairs. The distributed model, in which two related items share some of their features, would explain how when people with AD lose those attributes, semantic memory is impaired. There is a bottom-up inhibition of other semantic competitors, as their features are not distinct at the semantic level. Inhibition does not occur in the thematic condition because the processing of the thematically related pairs is based on co-occurrence and shared context, function, and space.

Experiment 3 showed that thematic priming for words of early acquisition is functional in the moderate stages of AD where the words share the same context

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preventing semantic impairment. These results converge with those of Perri et al. (2019) and Zhang et al. (2023), who argue that thematic relationships are highly dominant and resistant to memory degradation because they are based on complementary, rather than competing, sources of information. From early adulthood, thematic relationships involve less cognitive demand than taxonomic ones (Sass et al., 2009). This explanation is plausible, given the likelihood of encountering thematic words together in ordinary discourse, which may delay semantic deterioration. According to Mirman et al. (2017), while taxonomic links rely mainly on perceptual features, and as they are based on hierarchical members of a category, their processing involves structured and systematic cognitive mechanisms. Thematic links are based on co-occurrence, function, spatial, and temporal relationships that involve a more flexible and context-sensitive mechanism. It may also be a question of utility: thematic relationships are preserved because they are linked to daily activities ("water"–"soap" in the context of taking a bath) more than taxonomic distinctions, which are less relevant ("dog"–"cat").

It is important to mention that while most of our taxonomic pairs had zero associative strength, the combined pairs did have some strength ($M = 21.28$), and the thematic pairs had twice their strength ($M = 43$). This difference could contribute to the lack of connections we saw when presenting taxonomic links. Future research could control the presentation of two scenarios of associative strength to confirm the role of this factor.

The results for healthy older adults are consistent with the findings of Merck et al. (2023), as no differences between types of relatedness were found in the TA group. Healthy adults do not seem to experience a loss in semantic storage that can be experimentally detected.

The preferential-looking task with eye tracking reduces top-down implications by exploring semantic memory implicitly in people with TA and AD, and the study controlled some factors that could influence priming effects. Words of early acquisition were used, as research has shown that words are more accessible in semantic memory if they are acquired early (Cuetos et al., 2017; Silveri et al., 2002), are highly frequent (Thompson-Schill et al., 1999), or are familiar (Gainotti et al., 1996). The outcome confirms the differential response between taxonomic and thematic pairs of words in people with AD (Perri et al., 2019; Simoes Loureiro & Lefebvre, 2016) and shows a novel lack of effect of combined relationships, even those containing a thematic relationship to which people are sensitive when they are presented alone.

Limitations

There are a number of limitations in our study that should be noted. Given the novelty of the eye-tracking comprehension method, there are no other studies with which to compare our results in the contrast between one- and two-level relationships. The experimental design also mixed visual and auditory information; it is necessary to compare the results with a study employing a unimodal experimental design. Although in all cases we presented words of early acquisition, subtle differences in imageability (Cuetos et al., 2017), semantic richness (Duarte &

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Robert, 2014), animacy (McRae et al., 2005), and perceptual strength (Miceli et al., 2023), as well as variable degrees of association between primes and targets, could affect the semantic system in people with AD. Finally, the study population represented a vulnerable group during the post-COVID-19 pandemic, making recruitment challenging; as a result, we were unable to conduct a full range of cognitive assessments, including language tests, and our sample size was limited.

Conclusions

This study used an eye-tracking method to analyze how words are connected at the comprehension level in the mental lexicon of older adults diagnosed with moderate stages of AD, as compared with older adults with TA. This study thus provides an important contribution to the characterization of lexical networks in people with AD, semantic impairments with taxonomic pairs, and facilitation with referents sharing a context (thematic relationships). The outcome suggests caution in studies of people with AD that use words with two levels of relationships, since this may introduce a saturation effect. This study indicates a deterioration in the semantic system of people with moderate AD. The study provides findings that may be useful in the design of clinical tests and guidance for interventions.

Replication package. The material, data, and scripts that support the findings of this study are available at the Open Science Framework, at https://osf.io/zhfbq/.

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