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The processing of ambiguous words without context: Semantic activation, inhibition, selection and controlled retrieval in younger and older adults

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ABSTRACT

This study investigates how healthy aging affects four core semantic memory processes: activation, inhibition, selection, and controlled retrieval. Two experimental paradigms were adapted in French to assess these mechanisms: a Lexical Decision Task (LDT) using ambiguous and monosemic words to examine automatic activation and inhibition, and a Cue-to-Target Association Task (CTTAT) to evaluate executive processes such as selection and controlled retrieval. For this purpose, 100 older (66.94 ± 4.49) and 75 younger (26.64 ± 5.87) adults were tested.

Results from the LDT showed that both younger and older adults benefitted from semantic priming when processing dominant meanings and monosemic associates. In contrast, subordinate meanings and unrelated targets produced slower responses, suggesting the involvement of inhibitory mechanisms. These effects were consistent across age groups, indicating preserved early-stage activation and inhibition with aging.

In the CTTAT, results showed that participants were more accurate when associating based on perceptual features than on overall meaning. While older adults preserved controlled retrieval abilities, they showed vulnerability selection process, especially in the presence of semantic distractors. Overall, the findings indicate that aging selectively affects semantic selection, whereas activation, early inhibition, and controlled retrieval remain largely intact.

Together, these findings challenge global decline models of cognitive aging by showing selective effects on interference control. This work offers an integrated framework for assessing semantic control across the lifespan and lays the groundwork for future research on the interplay between automatic and controlled processes in semantic memory.

Contents

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List of Abbreviations

AD	Ambiguous Dominant (prime-target pair)
AS	Ambiguous Subordinate (prime-target pair)
BDI-II	Beck Depression Inventory, Second Edition
CTTAT	Cue-to-Target Association Task
FDR	False Discovery Rate
GDS	Geriatric Depression Scale
LDT	Lexical Decision Task
LSA	Latent Semantic Analysis
MAD	Median Absolute Deviation
MMSE	Mini-Mental State Examination
REML	Restricted Maximum Likelihood
RT	Reaction Time
SOA	Stimulus Onset Asynchrony
STAI	State-Trait Anxiety Inventory

1. Introduction

To perform a semantic task, individuals must retrieve relevant knowledge stored in semantic memory. This retrieval process involves a cascade of interrelated operations: the activation of conceptual representations and the automatic spread of this activation across related nodes; the inhibition of irrelevant or competing representations, and, when spontaneous retrieval fails, more controlled forms of semantic access such as selection and controlled retrieval. Understanding the dynamics of these mechanisms, and how they evolve across the lifespan, is central to advancing our models of semantic memory.

1.1. Semantic activation and inhibition

Activation and its spreading are usually conceptualized within the framework of network models, where concepts are linked by shared features or associations, and activation spreads based on semantic similarity (Anderson & Pirolli, 1984; Collins & Loftus, 1975; Collins & Quillian, 1969; Harris, 1954). This spreading activation is believed to be automatic, pre-conscious, and proportional to the strength and number of semantic links.

A distinction is often made between the automatic activation of concepts and the conscious access to these activated representations (Laisney et al., 2010; Mirman & Britt, 2014; Moss et al., 2005; Neely, 1977; Nozari, 2019; Warrington & Shallice, 1979). Although not universally accepted (Rapp & Caramazza, 1993), this dissociation is supported by neuropsychological evidence showing that frontal lesions can selectively impair retrieval while sparing automatic activation (Thompson-Schill et al., 2005, 1997, 1998).

Following activation, inhibitory mechanisms are recruited to manage competition among co-activated representations (Brown, 1979; Burgess et al., 1998; Copland et al., 2007; Raucher-Chéné et al., 2017; Simpson & Burgess, 1985). In the literature, a temporal distinction is often made between early, automatic inhibition, occurring within a few hundred milliseconds after stimulus onset, and later inhibition, which contributes to conflict resolution during conscious semantic access (Becker & Killion, 1977; Copland et al., 2007; Holderbaum et al., 2019; Neely, 1977, 1991). The present study primarily targets this latter stage.

This inhibition prevents bottom-up semantic interference and facilitates access to relevant targets, particularly in contexts of lexical ambiguity. Conceptually, this dynamic is also explained by *interactive activation and competition* frameworks (Grossberg & Schmajuk, 1987; McClelland et al., 2006; McClelland & Rumelhart, 1981) that capture the interactive balance between activation and inhibition: activation spreads across representational levels, while lateral inhibition mediates competition within a level. However we do not aim to test this model, but to use this architecture as a theoretical scaffold for interpreting how activation and inhibition jointly intervene in semantic processing.

1.2. Ambiguous words and priming

Ambiguous words offer a unique window into the dynamic balance between activation and inhibition during lexical-semantic access. Studies have shown that such words benefit from faster lexical decisions due to their multiple semantic representations (Kellas et al., 1988; Rodd et al., 2002). However, subordinate meanings require greater inhibitory effort to resolve competition (Bilenko et al., 2008; Gennari et al., 2007; Rodd et al., 2002).

According to the exhaustive access model (Simpson & Burgess, 1985), all meanings of an ambiguous word are activated in parallel, regardless of context. Dominant meanings are typically accessed more rapidly, while subordinate ones are subsequently inhibited to minimize processing cost (Copland et al., 2007). Thus, the comprehension of ambiguous words depends not on activation or inhibition alone, but on the flexible interplay between the two: activation enables rapid access to multiple meanings, while inhibition constrains this activation to select the most contextually appropriate interpretation.

To distinctly measure these processes, semantic priming paradigms using ambiguous words are particularly informative (Copland et al., 2007, 2003). Semantic priming reflects facilitation in processing a target word (e.g., *cat*) when it is preceded by a semantically related prime (e.g., *mouse*) (Balota & Lorch, 1986; Brunel & Lavigne, 2009; Forster, 1981; Hutchison et al., 2013; Lupker, 1984; Moss et al., 1994; Neely, 1977, 1991). This phenomenon is attributed to the automatic spreading of activation within semantic networks, typically observed with short stimulus onset asynchronies (SOAs) ranging from 150 to 500 ms (Altarriba & Basnight-Brown, 2007; Becker & Killion, 1977; Holderbaum et al., 2019). When ambiguous words are used in priming tasks (Copland et al., 2007, 2003), dominant meanings are accessed more rapidly than subordinate ones at short SOAs, reflecting automatic spreading activation. At longer SOAs (exceeding 500 ms), inhibitory mechanisms suppress the initially activated dominant meaning, thereby allowing the subordinate meaning to be (re)activated, particularly when supported by contextual information. Thus, ambiguity resolution reflects a temporal shift from automatic activation to controlled inhibition, consistent with the two-stage dynamic discussed in Section 1.1.

Neuroimaging studies further support this dissociation. Dominant meanings elicit reduced activation in temporal semantic areas, reflecting processing efficiency, whereas subordinate meanings recruit prefrontal regions such as the left inferior frontal gyrus (LIFG), implicated in conflict resolution and inhibition (Copland et al., 2007, 2003). Together, these findings support the view that semantic access to ambiguous words depends on a dynamic equilibrium between activation and inhibition, modulated over time and by executive control demands.

Finally, Thérouanne and Denhière (2004) stress that the difference between homonymy and polysemy can influence experimental results. Homonyms refer to distinct lexical entries that share the same form but have unrelated meanings (e.g., bark as “tree covering” vs. “dog sound”), whereas polysemous words correspond to some sort of semantically related senses within a single lexical entry. Thérouanne and Denhière (2004) underline that the presence or absence of semantic relatedness between meanings cannot be neglected in cognitive research on ambiguous words. Following this distinction, half of the ambiguous stimuli of the following protocol are homonyms and half are polysemous words.

1.3. Selection, controlled retrieval and association task

Beyond activation and inhibition, semantic access requires the recruitment of executive processes. Two such mechanisms have been distinguished: selection, which involved resolution of competition between simultaneously activated representations, and controlled retrieval, which initiates the search for less salient or weakly associated concepts (Badre et al., 2005; Badre & Wagner, 2002; Moss et al., 2005; Thompson-Schill et al., 1997; Wagner, 2002; Wagner et al., 2001).

Selection becomes particularly demanding when distractors share semantic features with the target or when tasks emphasize fine-grained semantic dimensions (e.g., color, size). Experimental manipulations such as increasing the number of response options or introducing competitive distractors have been shown to elevate selection demands (Badre & Wagner, 2002; Moss et al., 2005; Thompson-Schill et al., 1997; Wagner, 2002; Wagner et al., 2001)

Controlled retrieval, in contrast, is required when automatic activation does not suffice, such as in the case of weak associations or underdetermined contexts (Gabrieli et al., 1998; Poldrack et al., 1999). Unlike selection, it appears less sensitive to interference but more dependent on semantic knowledge breadth. It may also be hypothesized that deliberately accessing the subordinate meaning of a homonymous word engages controlled retrieval, given that such meanings are typically more weakly associated and activated.

Several authors (Badre et al., 2005; Bunge et al., 2002; Wagner et al., 2001) distinguish selection from controlled retrieval, while acknowledging possible overlap. In an association task, they identified the two components through four design manipulations (see Fig. 1): (1) judgment specificity (broad vs. specific associations), (2) semantic link strength (strong vs. weak), (3) number of response options (2 vs. 4), and (4) distractor type (competitive vs. non-competitive). Longer response times occurred with specific judgments, weak links, more options, and competitive distractors. Factor analysis showed selection was tied to distractor type, specificity, and link strength, while non-selection was tied only to the latter two.

Fig. 1. Representation of selection and non-selection components among the manipulations of the Association Task explained in Badre et al. (2005).

1.4. Aging and semantic control

Aging does not affect all memory systems equally. Although episodic memory, which relies on the retrieval of contextually bound, event-specific information, typically declines with age, semantic memory, the store of conceptual and lexical knowledge, tends to remain relatively preserved (Grady, 2012; Nyberg et al., 2012). However, growing evidence indicates that specific subprocesses of semantic retrieval may be differentially sensitive to aging.

While the general structure and accessibility of semantic knowledge are maintained (Burke & Shafto, 2004; Wulff et al., 2022), older adults may show subtle alterations in automatic activation spreading, reflected in slower or less efficient semantic priming. Meta-analytic findings support a significant age effect on priming accuracy and latency, whereas electrophysiological indices such as the N400 reveal less pronounced differences (Joyal et al., 2020). These results suggest that the dynamics of semantic activation, rather than semantic knowledge itself, may be affected by aging.

Age-related changes in executive and control processes have also been observed. Although (Rey-Mermet & Gade, 2018) proposed that cognitive inhibition is not globally impaired with age, other studies report that the ability to resolve competition among co-activated representations, namely semantic selection, declines in older adults (Hoffman & Morcom, 2018; Wu & Hoffman, 2023). In contrast, controlled retrieval, which requires deliberate access to less dominant semantic information, appears to remain relatively preserved (Hoffman, 2018; Wu et al., 2023).

Given these partly conflicting findings, the present study aimed to clarify how healthy aging affects key subprocesses of semantic memory retrieval, namely, activation, inhibition, selection, and controlled retrieval, particularly in the context of processing ambiguous words. To this end, we adapted and combined two experimental tasks (in French): a lexical decision task with semantic priming task using ambiguous words (LDT, Copland et al. (2003), designed to measure activation and late inhibition) and a cue-to-target association task (CTTAT, Badre et al. (2005)) designed to manipulate semantic control demands. These paradigms provide complementary insights into how aging influences both automatic and controlled aspects of semantic processing under conditions of ambiguity.

2. Method

Two experimental tasks will be used to measure activation spreading, inhibition, selection, and controlled retrieval in a group of young and older adults.

Activation spreading and inhibition will be assessed using a lexical decision task with priming on ambiguous words (LDT), designed based on Copland et al. (2007) and Labalestra (2018).

Selection and controlled retrieval will be measured using a semantic rule-based cue to target association task (CTTAT), inspired by designs from Badre and Wagner (2002) and Hoffman (2018).

These paradigms are novel in the context of cognitive aging: the LDT has never been used for this purpose, and the CTTAT has not been applied in French nor with ambiguous words.

2.1. Sample size justification

For the sample size based on the LDT, we conducted an a priori power analysis for a generalized linear mixed model through simulations, following Brysbaert and Stevens (2018) recommendations and using the R package lmer (Kuznetsova et al., 2015). The results indicated that a sample of seventy-five participants provided a power of 0.79, and a minimum sample of one hundred participants provided a power of 0.90. For the CTTAT, the sample size was calculated using the R package pwr (Champely et al., 2017) for a desired a priori power of 0.80, an expected mean effect size of d = 0.25, and a significance level of $p < 0.05$, following Langenberg et al. (2023) recommendations for a repeated-measures ANOVA design. It indicates that at least sixty-eight participants per group were necessary. The details are provided in Section 2 of the supplementary material.

Sample sizes calculation codes are available in S.3 (Sample size Justification).

2.2. Participants

A total of 175 healthy adults were recruited between June 2021 and June 2024: 100 older adults (M = 66.9, SD = 4.49) and 75 younger adults (M = 26.64, SD = 5.87). Recruitment was conducted via written announcements. The study received ethical approval from the central ethics committee of ULB Erasme Hospital (Belgium) and complied with the Declaration of Helsinki. Informed consent was obtained from all participants.

Exclusion criteria included neurological, psychiatric, or developmental disorders, history of stroke, or head trauma. One younger participant withdrew during testing. Eleven additional participants (ten older, one younger) were excluded due to atypical task behaviors. Final sample demographics are detailed in Table 1. In this table, all results are presented as raw scores, except for the Stroop interference score (Jensen, 1965), which was calculated using the following ratio:

$$\text{Interference score} = \frac{\text{Interference time} - \text{naming time}}{\text{Naming time} + \text{Interference time}}.$$

Table 1
Sample demographic data and general cognitive assessment.

	Older group	Younger group	p
N	100	74	
Woman (%)	61 (61.0)	42 (56.8)	0.684
Right-handed (%)	88 (88.0)	59 (79.7)	0.201
Age	66.94 (4.49)	26.64 (5.87)	<0.001
Education	13.24 (2.11)	14.16 (1.19)	0.001
BDI 2 (/63)		8.88 (7.28)	
GDS (/30)	4.15 (4.00)		
Anxiety trait (Stai)	37.38 (10.89)	42.51 (10.93)	0.003
Anxiety state (Stai)	33.01 (12.76)	33.18 (11.41)	0.930
Semantic fluency (2 min.)	29.48 (7.85)	39.39 (9.18)	<0.001
Phonemic fluency (2 min.)	23.95 (7.31)	27.49 (7.37)	0.002
Stroop interference score	0.30 (0.10)	0.20 (0.07)	<0.001
MMSE	28.98 (1.09)		

Note: BDI2 (Beck et al., 1996): Beck Depression Inventory revised; STAI: Spielberger Test Anxiety Inventory (Spielberger, 2010). All scores are raw scores, except for Stroop interference scores, which were computed as follows:
$\text{Interference score} = \frac{\text{Interference time} - \text{naming time}}{\text{Naming time} + \text{Interference time}}$.

2.3. General psychocognitive assessment

The participants completed a general assessment of cognitive function and domain-general executive abilities. They completed the tasks of phonemic and semantic fluency (within two minutes). Semantic fluency requires generating words belonging to a specific category and relies more on breadth of semantic knowledge, while in the phonemic fluency the participant must produce words starting with a specific letter and relies more on the executive contribution to semantic processing. The domain-general inhibition was measured using the Stroop test (Jensen, 1965). For both groups, the anxiety was tested (as state or trait) with the Spielberger's State and trait anxiety inventory (Spielberger et al., 1971) and the presence of depressive symptoms was excluded based on the results at the Beck depression inventory (BECK et al., 1961) for the younger participants and the geriatric depression scale (Yesavage, 1988) for the older participants. In the group of older adults, cases of possible cognitive impairment was excluded based on the Mini-mental State Evaluation (MMSE) (Folstein et al., 1975).

To assess the four processes of semantic memory (activation, inhibition, selection, controlled retrieval), two original tasks were developed in French: A Lexical Decision Task (LDT) using ambiguous and monosemous words to measure activation and inhibition; A Cue-to-Target Association Task (CTTAT) to measure selection and controlled retrieval. Both tasks were administered on-screen using the Testable.org platform. The order of task presentation was counterbalanced across participants.

2.4. Test of semantic activation and semantic inhibition: Lexical Decision Task (LDT)

The LDT employed an original corpus of French words (Table S3). Prime-target pairs were categorized based on semantic relationships into four tiers. Four conditions were defined: AD: Ambiguous prime – dominant associate (measuring semantic activation); AS: Ambiguous prime – subordinate associate (measuring semantic inhibition, as accessing subordinate meaning requires suppression of the dominant one); M: Monosemous prime – semantic associate (baseline for activation); NR: Unrelated prime – unrelated target.

The sequence of stimuli, presented in Fig. 2 included a fixation cross (200 ms), a prime word (500 ms), a blank screen (500 ms), and a target stimulus. The target was either a real French word or a non-word and remained on the screen until the participant responded. Participants were instructed to ignore the first word and determine whether the second was a valid French word ("yes") or not ("no"), responding as quickly as possible while minimizing errors. They were required to keep both hands on two designated computer keys, each marked with

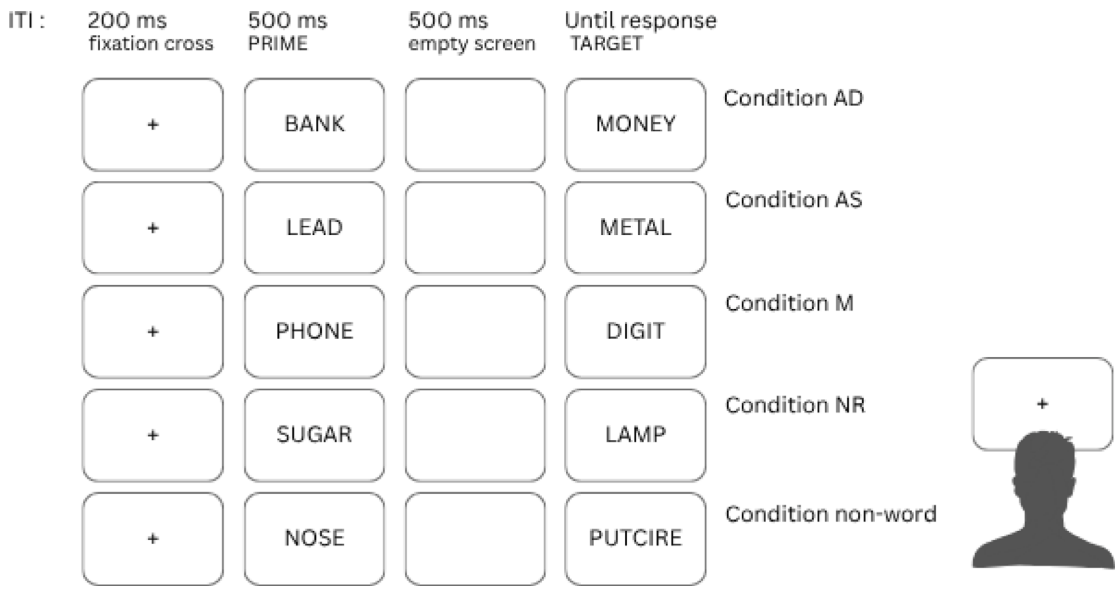

Fig. 2. Presentation of the sequence of screens in the Lexical Decision Task (LDT).

Table 2
Example of stimuli and counterbalancing between versions.

	Prime	Target	
Example version 1			
AD (8 trials)	e.g. BANK	e.g. MONEY	Counterbalanced
AS (8 trials)	e.g. RIGHT	e.g. DIRECTION	Counterbalanced
M (16 trials)	e.g. PHONE	e.g. DIGIT	Counterbalanced
NR (32 trials)	e.g. GRASS	e.g. COMPUTER	Counterbalanced
Fill-in NR (20 trials)	e.g. SUGAR	e.g. PLANT	Not counterbalanced
Non-words (84 trials)	e.g. NOSE	e.g. PUTCIRE	Equal among versions
Example version 2			
AD (8 trials)	e.g. RIGHT	e.g. CORRECT	Counterbalanced
AS (8 trials)	e.g. BANK	e.g. RIVER	Counterbalanced
M (16 trials)	e.g. SAVING	e.g. MONEY	Counterbalanced
NR (32 trials)	e.g. PHONE	e.g. DIRECTION	Counterbalanced
Fill-in NR (20 trials)	e.g. PLANT	e.g. SUGAR	Not counterbalanced
Non-words (84 trials)	e.g. NOSE	e.g. PUTCIRE	Equal among versions

Note. Each version includes 8 AD trials, 8 AS trials, 16 M trials, 32 NR trials, 20 Fill-in NR trials, and 84 Non-word trials. The first four categories were counterbalanced across four versions to ensure that each participant saw a different subset of stimuli. The Fill-in NR items were not counterbalanced, and the Non-word items were evenly distributed among versions. Participants were assigned versions in a rotating order (Participant 1: Version 1; Participant 2: Version 2; Participant 3: Version 3; Participant 4: Version 4; Participant 5: Version 1; etc.).

a colored sticker labeled “O” (yes) or “N” (no). The “O” response key was always assigned to the participant’s dominant hand. Before the main task, each participant completed 14 training trials to familiarize themselves with the sequence, instructions, and response keys. During training, they received feedback, and the instructions were clarified if needed. No feedback was provided during the experimental trials. Each participant completed 168 test trials, with word presentation randomized by the program. Each version included: 8 AD, 8 AS, 16 M, 32 NR, 20 filler unrelated pairs, and 84 non-word trials. Participants were debriefed about potential ambiguity but none reported awareness of the manipulation. The main difference between our version of the task and the previous work of Copland et al. (2003) is the inclusion of a monosemic condition of semantic association and the composition of a new original corpus of words as the task had to be provided in French.

We assembled our corpus of French ambiguous words from free-association norms, drawing dominant and subordinate meanings (Thérouanne & Denhière, 2004: values for younger adults). To align materials with our target population, we additionally collected polarity judgments from older participants and retained only triads (ambiguous word–dominant meaning–subordinate meaning) showing a significant dominance contrast; full procedures, statistics (Friedman and Wilcoxon tests), and the complete word lists appear in the Supplementary Materials (1.2.1 Corpus of ambiguous words). Because the semantic structure of ambiguity matters for cognitive processing, and prior work cautions. To follow Thérouanne and Denhière (2004) recommendation to respect the homonymy–polysemy distinction when constructing materials we balanced the set so that half the items are homonyms and half are polysemesous words. In the task, monosemous items were selected through an empirical inter-judge procedure ensuring they evoked only one salient meaning. The unrelated condition was constructed through a Latin-square counterbalancing of lexical materials across lists to control for item-specific variables.

Table 2 describes the counterbalancing across the four versions, with examples provided for two of them. The rationale for control of psycholinguistic attributes as concreteness, frequency, orthographic neighborhood, and length, as well as the strength of semantic association (measured using Latent Semantic Analysis [LSA]; Landauer et al., 1998), is detailed Table 3.

The automatic semantic priming effect (SPE) depends on the stimulus onset asynchrony (SOA), with short SOAs (150–500 ms) reflecting automatic spreading of activation, whereas longer SOAs (>500 ms) engage additional controlled processes related to expectancy and selection. At long SOAs (around 1000 ms) (Altarriba & Basnight-Brown, 2007; Neely, 1977, 1991), as shown by Copland et al. (2003), ambiguous-word priming (e.g., right-correct vs. right-direction) reveals both facilitation for dominant meanings and inhibitory control for subordinate ones, evidenced by differential neural activity in temporal and prefrontal regions. These results indicate that beyond automatic spreading, semantic processing also involves executive mechanisms such as inhibition of internally activated but irrelevant meanings. When SOA exceeds 1200 ms, however, automatic activation can no longer be isolated, as successive cycles of controlled activation and selection dominate processing (Neely et al., 2010). For all these reasons, the SOA in the present experiment was set at 1000 ms.

2.5. Test of semantic selection and controlled retrieval with a Cue to Target Association Task (CTTAT)

The CTTAT is a semantic association task designed to assess executive components of semantic control, particularly selection and

Table 3
LDT: Psycholinguistic values and semantic associations by conditions on all items.

	AD	AS	M	NR	ANOVA: F, p-value
All items (N by version)	30 (8)	30 (8)	62 (16)	124 (32)	
Frq. Book (prime)	23.26 (24.70)	24.28 (24.79)	28.26 (35.6)	33.22 (51.65)	F = 0.66, p = 0.55
Frq. Book (target)	48.38 (40.76)	27.99 (25.82)	36.87 (33.79)	34.29 (34.26)	F = 2.08, p = 0.10
Frq. Film (prime)	18.93 (21.33)	17.66 (21.76)	19.77 (28.9)	20.8 (28.9)	F = 0.13, p = 0.94
Frq. Film (target)	63.22 (109)	31.46 (46.45)	42.62 (63.76)	33.08 (56.2)	F = 1.95, p = 0.12
nb letters (prime)	5.59 (1.52)	5.77 (1.62)	6.71 (1.86)	6.38 (1.69)	F = 4.32, p = 0.009
nb letters (target)	6.22 (1.56)	6.03 (1.85)	6.04 (1.85)	6.55 (1.91)	F = 1.40, p = 0.24
Orth.ngb (prime)	3.84 (4.5)	3.38 (4.13)	2.5 (3.75)	2.64 (3.49)	F = 2.63, p = 0.30
Orth.ngb (target)	3.25 (3.70)	3.29 (4)	3.71 (4.18)	2.8 (4.11)	F = 0.67, p = 0.60
Concreteness (prime)	3.79 (1.07)	3.74 (1.16)	3.78 (1.10)	3.86 (1.05)	F = 0.08, p = 0.96
Concreteness (target)	3.86 (1.06)	3.67 (1.1)	3.70 (1.06)	3.98 (0.90)	F = 1.45, p = 0.23
Semantic association (LSA)	0.34 (0.19)	0.12 (0.07)	0.27 (0.13)	0.1 (0.11)	M, PD < PS, NR : p < 0.001

controlled retrieval. On each trial, participants are presented with a cue word and must select, among several response options, the word that best matches the cue according to a specified semantic criterion. This version of the CTTAT follows the authors' previous work (Badre et al., 2005; Badre & Wagner, 2002; Hoffman & Morcom, 2018; Thompson-Schill et al., 1997; Wagner, 2002; Wagner et al., 2001) presented in the theoretical introduction, but with three main differences. Firstly, we replaced the strong/weak semantic associate condition with ambiguous words, intended to be associated with a synonym corresponding to their dominant or subordinate meaning. Secondly, the presence versus absence of a semantically related distractor was systematically manipulated across all CTTAT conditions (dominant, subordinate, and feature-based associations), with related distractors appearing in half of the trials in each condition. Thirdly, while previous tasks were in English, we constructed our original corpus using French words. For the synonym association instruction, twenty-eight ambiguous words from the LDT corpus are utilized. In line with theoretical accounts emphasizing that perceptual features such as color and size differ in their salience, discriminability, and contextual dependence, we deliberately balanced the feature-based association condition across these two dimensions (Mukherjee et al., 2021). This design ensured that both types of perceptual information were equally represented, as did Badre et al. (2005) in the original design. Stimuli characteristics (concreteness, imageability, frequency, length, LSA values) are detailed in Table S5.

Each participant completed 60 trials: 14 dominant synonyms, 14 subordinate synonyms, 16 size-based, and 16 color-based trials. The task was implemented on a testable platform (Rezlescu et al., 2020) and conducted on-screen, with response keys 1, 2, or 1, 2, 3, 4, aligned on the center of the keyboard. For each block, 3 training trials were provided, with feedback to ensure understanding of the instructions. Participants did not encounter difficulties in comprehending the instructions (illustrated in Fig. 3).

On each trial, a cue word appeared at the top of the screen, followed by two or four response options displayed below. Participants selected the word whose meaning or feature was closest to that of the cue. Each trial had one correct answer. In all conditions, one distractor was semantically related to the cue in half of the trials.

In conditions 1 and 2, participants chose the word sharing the same meaning with the cue (e.g., Perception – sensation). The two subconditions differed in the type of cue word: one used dominant ambiguous words (primary meaning targeted, e.g., sensation), while the other used subordinate ambiguous words (less frequent meaning targeted, e.g., *Glace* meaning "mirror" rather than "ice cream"). These subconditions were randomly intermixed, and participants were not informed of the ambiguity manipulation.

Conditions 3 and 4 involved feature-based associations. In Condition 3, participants selected the item closest in typical physical size to the cue (e.g., Caillou – Dent [pebble – tooth]); in Condition 4, they selected the item sharing the same typical color (e.g., Coccinelle – Groseille [ladybug – currant]).

In the analysis, the contrast between Conditions 1 and 2 (dominant vs. subordinate ambiguous words) was designed to increase the participants' need to engage in controlled semantic retrieval. In the dominant condition, the relationship between the cue and the correct response relies on the most accessible and frequent meaning of the ambiguous word. In contrast, the subordinate condition required the retrieval of a less dominant or weakly associated meaning, which is typically less automatically activated (Rodd et al., 2002). This manipulation is proposed as conceptually parallel to the strong vs. weak semantic association contrast used in the original paradigm of Badre et al. (2005), where the authors demonstrated that retrieving weak associations engages controlled retrieval mechanisms supported by the left ventrolateral prefrontal cortex.

The selection process was manipulated through three variations according the classical design of Badre et al. (2005). First the instruction type varied between global association (condition 1 and 2) and feature-based association (condition 3 and 4). Secondly, selection was also increased by the presence of a meaningful distractor, and, thirdly, with variations in the set size (one vs. three distractors). All three modulate the degree of competition among semantic representations.

2.6. Procedure

Participants first completed the cognitive assessment, followed by the two experimental tasks in counterbalanced order but for both tasks accuracy and response times (RT) were recorded. No time limits were imposed. Participants sat 70 cm from the screen. Total testing time ranged from 50 to 60 min.

2.7. Statistical analysis

The collected data of both experimental tasks were analyzed based on the proportion of accuracy and RT; the data extracted from the testable software were pre-processed with Python (Van Rossum & Drake, 1995) libraries Os, Panda (McKinney, 2011) and NumPy (Harris et al., 2020; McKinney, 2010). The pre-processed data were imported into R studio (Allaire, 2012) for statistical analysis.

For both tasks, RT are measured only for the correct answers and the remaining RT were then screened for outliers using the median absolute deviation (MAD) method (Leys et al., 2013) placing the threshold of the outliers at a value of three, a very conservative threshold under Miller's criteria (Miller, 1991).

RT were transformed in z scores (each participant compared to himself) as recommended in Luce (1991) with

$$z = \frac{RT - \mu}{\sigma}$$

2.7.1. Analysis of the LDT results

Only the responses from the conditions of interest were analyzed. All fill-in items and non-words were excluded. After preprocessing, 2.74% of the data were excluded due to wrong answers, and 0.41% were removed as RT outliers.

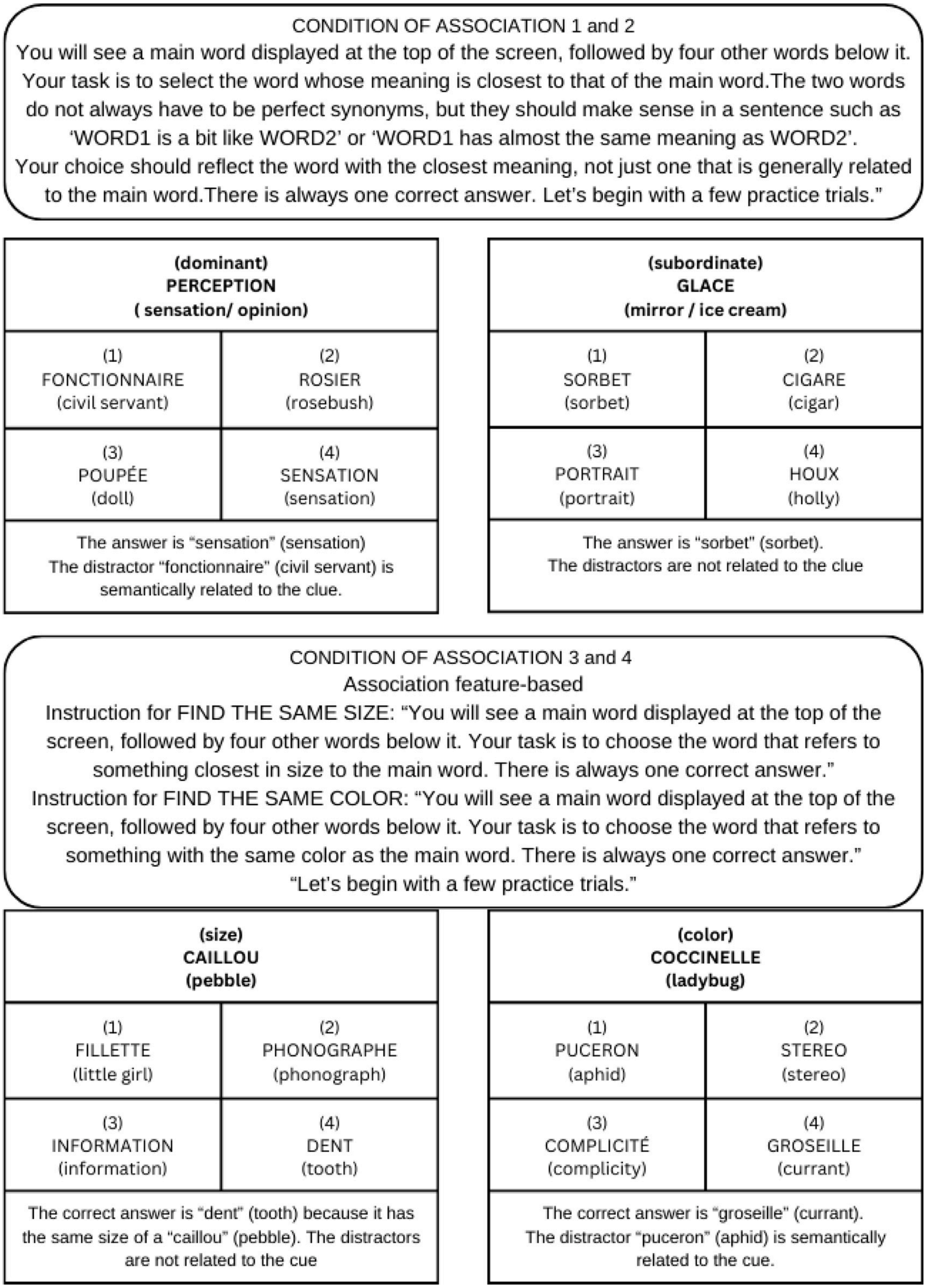

Fig. 3. Presentation of the Cue to Target Association Task (CTTAT).
Note. In these examples, words in uppercase correspond to the items as they appeared in French in the task. The lowercase words in parentheses provide the English translation (which did not appear in the task and is included here solely for the reader's convenience).

Remaining data were analyzed using linear mixed models (LMMs) with REML estimation (see recommendation of Baayen et al. (2008), Brown (2021), Brysbaert and Stevens (2018), Hohenstein et al. (2010) and Stefaniak (2018)).

The Z scores were analyzed using linear mixed-effects models including *condition* and *group* as fixed effects. The initial random-effects structure included random intercepts for both participants and prime–target pairs (1 + condition | participant) + (1 + condition | primetarget).

However, model diagnostics based on `rePCA()` indicated that the participant-level intercept contributed no meaningful variance, which is expected given that RTs were standardized within participants (z-scoring).

To avoid overparameterization and singular fit issues (Meteyard & Davies, 2020), the random-effects structure was simplified to retain only a random intercept for prime–target pairs. The final model was therefore:

$$model = \texttt{lmer}(z - score \sim condition \times group + (1 \mid prime - target), \text{REML} = \text{TRUE})$$

DHARMa diagnostics revealed no evidence of heteroscedasticity and only minor deviations in the tails of the residual distribution, indicating an overall satisfactory model fit. Further details on the model diagnostics are provided in Supplementary Material 4.1.1 *(Assumptions of LMM)*.

Anova on the model was a type III Analysis of Variance Table with Satterthwaite's method (Kuznetsova et al., 2017). Post-hoc pairwise comparisons used *False Discovery Rate (FDR)* correction (Benjamini & Hochberg, 1995). Effect sizes for the analyses of variance were estimated using *partial eta squared* (η_p^2), computed from the sum of squares of each effect in the model. For post hoc comparisons, differences between conditions were quantified using *Cohen's d*, calculated from the estimated marginal means (EMMs) derived from the mixed-effects models (Lenth, 2022).

The raw outputs of these analysis are provided in Supplementary material, section*4.1 LDT - Z scores of RT - Model Diagnostic - LLM - ANOVA - Post-Hoc*.

2.7.2. Analysis of the CTTAT results

For the CTTAT results, 18.35% of the data were excluded due to wrong answers, and 5.59% were removed as RT outliers.

A subsequent examination of the norming and pilot data indicated that, for three items (réflexion, note, and baleine), the polarity of dominant and subordinate meanings differed between younger and older participants. To ensure comparability of semantic interpretations across age groups, these three items were excluded from the analyses.

Participants' performance accuracy and reaction times (in z-scores) were analyzed using mixed-effects modeling. Accuracy data were analyzed with a generalized linear mixed-effects model (GLMM) assuming a binomial error distribution and a logit link function, whereas reaction times were analyzed with a linear mixed-effects model (LMM) applied to z-scored RTs, in order to control for individual differences in overall response speed. Both models were fitted using the lme4 package in R (Bates et al., 2015). Models were estimated using the bobyqa optimizer with an increased iteration limit (100,000) to ensure convergence. The significance of fixed effects was assessed using Wald z-tests (for the GLMM) and t-tests (for the LMM). Odds ratios were obtained by exponentiating the fixed-effect coefficients to express the results in terms of response probabilities.

This first level of analysis explored the selection process, influenced by the type of instruction (global association vs. feature-based association), the distractor condition (presence vs. absence of a meaningful distractor), and the set size (one vs. three distractors). For the accuracy analysis, the dependent variable was the binary response variable correct (1 = correct, 0 = incorrect). For both analyses, categorical predictors were recoded and centered using effect coding (±0.5) to facilitate interpretation of main effects and interactions. Specifically, Type was coded as +0.5 for the global condition and –0.5 for the feature condition; Distractor as +0.5 for the related distractor condition and –0.5 for the unrelated distractor condition; Set Size as +0.5 for trials with three distractors and –0.5 for trials with one distractor; and Group as +0.5 for young participants and –0.5 for older participants. Both models included Group and its interactions with Type, Distractor, and Set Size as fixed effects. Random effects consisted of random intercepts and slopes for participant (for Type, Distractor, and Set Size) and random intercepts for cue, accounting for between-participant and between-item variability.

A second level of analysis focused on the controlled retrieval process, examining only trials from the global association condition, in which participants retrieved the same global meaning. This model tested whether controlled retrieval varied as a function of association dominance (dominant vs. subordinate meanings), distractor condition (related vs. unrelated distractor), and set size (one vs. three distractors), as well as their possible interactions with age group (young vs. older adults). Equally to the other model, all predictors were contrast-coded (±0.5) and entered simultaneously to assess potential group differences and interaction effects. Random intercepts and slopes were specified for participants, and random intercepts for items (cues), to account for individual and item-level variability.

2.7.3. Analysis of correlations among index

To examine the relationships among associative structure and executive functioning, Pearson correlations were computed between all relevant behavioral indices. The dataset was created by merging the experimental measures with participants results at the stroop test and the fluency tasks. The variables included: performance on the phonological and semantic fluency tasks, the interference score from the Stroop task, priming effects from the LDT under the M, AS, and AD conditions, mean response times in the association task for global and feature-based associations, indices representing response times when the distractor was semantically related or unrelated, and association measures reflecting whether global associations were made according to dominant or subordinate semantic meanings.

All pairwise Pearson correlations were computed using the `rcorr` function from the `Hmisc` package. Resulting *p*-values were adjusted for multiple comparisons using the Benjamini–Hochberg false discovery rate (FDR) correction, and the adjusted values were compiled into an adjusted correlation matrix.

2.8. Transparency and openness

The list of items of the experimental tasks and the psycholinguistics data about the items, the scripts and the output for the analyses of all the experiments of the present study are available on OSF. The experimental tasks were built with the Online testing platform Testable.org (Rezlescu et al., 2020) and tasks are available (LDT; CTTAT). This study was not preregistered. The data were pre-processed with Pycharm 2024.1 version in the Community Edition released under the Apache License and with the Pandas (McKinney, 2011), Os and Numpy (Oliphant et al., 2006) libraries. The statistical analysis were led in R with the R studio framework version 2024.04.2 Build 764 (Allaire, 2012), and Jasp statistical software version 0.18.3.0 (Love et al., 2019). All data, program code, and other methods developed by others are referenced in the text and listed in the references section. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study.

3. Results

3.1. Test of semantic activation and inhibition: Lexical Decision Task (LDT)

Table 4 presents mean RT and standard deviation of every priming condition and their correspondance in z score.

The Type-III ANOVA revealed a significant main effect of Condition ($F_{(3,\ 221.7)} = 4.26$, $p = 0.006$, $\eta_p^2 = 0.06$), but no main effect of Group ($F_{(1,\ 9630.1)} = 0.04$, $p = 0.845$, $\eta_p^2 < 0$) and no Condition × Group interaction ($F_{(3,\ 9630.8)} = 0.82$, $p = 0.481$, $\eta_p^2 < 0$). This indicates that task performance differed across conditions, but these effects were comparable between groups. Pairwise post-hoc comparisons (Table 5) confirmed that NR differed significantly from both M (estimate = −0.141, SE = 0.057, $p = 0.040$, *Cohen's* $d = 0.006$) and AD (estimate = −0.219, SE = 0.071, $p = 0.014$, *Cohen's* $d = 0.01$). All other contrasts were non-significant (all $p > 0.12$), and standardized effects were very small except for the difference between AD and AS (*Cohen's* $d = 0.01$). These results indicate that the M and AD conditions both showed a

Table 4
Means and standard deviation of reaction time in LDT.

Condition	Older group		Younger group	
Mean (SD)	RT	Z scores	RT	Z scores
M	863 (250)	−0.06 (1.00)	744 (242)	−0.09 (0.95)
AD	862 (253)	−0.1 (0.97)	732 (242)	−0.12 (0.98)
AS	878 (255)	−0.02 (0.96)	765 (251)	0.04 (0.98)
NR	883 (257)	0.05 (0.99)	796 (261)	0.06 (1.01)

M = monosemic, AD = ambiguous dominant, AS = ambiguous subordinate, NR = non-related.

Table 5
Post-hoc comparisons (EMMeans).

Contrast	Estimate	SE	p-value	Cohen's d
M – AD	0.078	0.079	0.389	0.004
M – AS	−0.091	0.079	0.375	−0.005
M – NR	−0.141	0.057	0.040*	−0.006
AD – AS	−0.169	0.090	0.122	−0.011
AD – NR	−0.219	0.071	0.014*	−0.011
AS – NR	−0.050	0.071	0.477	−0.003

Note: Comparative analysis of Cohen's d, t ratios, and p values for younger and older groups across conditions. p significance levels — $p < 0.05$: *; $p < 0.01$: **; $p < 0.001$: ***.

priming effect, as expected, whereas the AS condition did not, which is consistent with the assumption that an inhibition process follows initial activation.

Finally, random-effects estimates showed substantial variability across items (prime–target pairs; Var = 0.123), leading to a boundary (singular) fit, while residual variance was 0.882. The model converged normally (optimizer code 0), and scaled residuals were well distributed (median ≈ −0.16; range −3.28 to 3.48). This confirms that the model fit was stable and that residuals met assumptions of normality and homoscedasticity.

3.2. Test of semantic selection and controlled retrieval with a Cue to Target Association Task (CTTAT) – Selection

Accuracy for both groups is presented in Table 6. According to the conditions enhancing selection, the generalized linear mixed-effects model revealed several significant effects. Participants in the young group performed overall more accurately than the older group ($\beta = 0.55$, $SE = 0.15$, $Z = 3.81$, $p < 0.001$). A main effect of instruction type was observed, with lower accuracy in the global condition compared to the feature-based condition ($\beta = -1.12$, $SE = 0.34$, $Z = -3.26$, $p = 0.001$). There was also a main effect of set size, indicating that accuracy decreased when three distractors were present compared to a single distractor ($\beta = -0.33$, $SE = 0.15$, $Z = -2.20$, $p = 0.028$).

Two significant interactions with group emerged. The *Group × Type* interaction was significant ($\beta = -1.08$, $SE = 0.19$, $Z = -5.68$, $p < 0.001$). The *Group × Distractor* interaction was also significant ($\beta = 0.46$, $SE = 0.13$, $Z = 3.56$, $p < 0.001$), indicating that the presence of a meaningful distractor impaired performance more strongly in older participants than in younger ones. No other main or interaction effects reached significance.

Regarding the reaction time, analyzed in z-scores; a significant main effect of Distractor was observed ($\beta = 0.27$, $SE = 0.09$, $t(84.25) = 2.82$, $p = 0.006$), indicating lower performance when distractors were present. There was also a strong *Group × Type interaction* ($\beta = 0.60$, $SE = 0.08$, $t(182.53) = 7.52$, $p < 0.001$), showing that the effect of Type of instruction differed between groups. The global-feature difference was larger for younger participants: younger adults performed quicker in the global association condition than in the local one, whereas this effect was attenuated in older adults. No other main effects or interactions reached significance for reaction times.

3.3. Test of semantic selection and controlled retrieval with a Cue to Target Association Task (CTTAT) – Controlled retrieval

To assess controlled retrieval, we examined only trials from the global association condition, focusing on the contrast between dominant and subordinate meanings. Proportion of accuracy of both groups in this condition are presented in Fig. 4. The model included additional predictors (distractor condition and set size) and their interactions with age group as control factors.

For accuracy, the generalized linear mixed-effects model revealed no significant main effect of dominance ($\beta = -0.07$, $SE = 0.53$, $z = -0.13$, $p = 0.90$), indicating that retrieval success did not differ between dominant and subordinate meanings. No interaction effects within dominance and any other condition were significant.

For reaction times, presented in Fig. 5, (z-scores), the linear mixed-effects model likewise showed no effect of dominance ($p > 0.80$). However, responses were overall faster in young adults ($\beta = 0.30$, $SE = 0.05$, $t(78.60) = 5.57$, $p < 0.001$) and slower when three distractors were presented ($\beta = -0.27$, $SE = 0.05$, $t(78.08) = -4.87$, $p < 0.001$). No other effects reached significance.

3.4. Correlations among index

Correlation analyses revealed that both fluency measures were significantly correlated with the *feature* index (Ph.F: $r = -0.31$, $p = 0.014$; Sem.F: $r = -0.28$, $p = 0.022$) and with the *global* association index (Ph.F: $r = 0.31$, $p = 0.013$; Sem.F: $r = 0.27$, $p = 0.022$).

Furthermore, both phonological and semantic fluency scores were positively related to the proportion of *dominant associations* (Ph.F: $r = 0.29$, $p = 0.022$; Sem.F: $r = 0.26$, $p = 0.029$), whereas their correlations with *subordinate associations* were weaker and nonsignificant (Ph.F: $r = 0.25$, $p = 0.054$; Sem.F: $r = 0.20$, $p = 0.122$). No other significant correlations were observed.

4. Discussion

This study investigated the effects of healthy aging on four semantic memory processes: activation, inhibition, selection, and controlled retrieval. Using two experimental paradigms (LDT and CTTAT) we compared younger and older adults' performance. This multidimensional approach was designed to capture both automatic and executive aspects of semantic control. The LDT primarily assessed automatic activation and inhibition processes through semantic priming, while the CTTAT targeted higher-level control mechanisms such as selection and controlled retrieval under varying levels of interference. The complementary nature of these two paradigms provides an integrated view of semantic functioning across the lifespan.

The main findings are twofold. First, semantic inhibition as measured through priming effects on ambiguous words was not significantly impaired in older adults. Both age groups benefited from facilitation when the prime was semantically linked to the dominant meaning, and showed reduced facilitation when the prime was linked to the subordinate meaning.

Second, age-related differences were evident in the association task: older adults maintained high accuracy levels but were more sensitive

Table 6
Accuracy (mean and sd) by Group, type of instruction, distractor, and set size.

Type of instruction	Distractor	Set size	Older		Younger	
			Mean acc	SD acc	Mean acc	SD acc
Feature	Non related	1	0.910	0.287	0.971	0.168
Feature	Non related	3	0.871	0.335	0.944	0.229
Feature	Related	1	0.838	0.369	0.933	0.250
Feature	Related	3	0.825	0.380	0.932	0.252
Global	Non related	1	0.754	0.431	0.773	0.420
Global	Non related	3	0.734	0.442	0.653	0.476
Global	Related	1	0.729	0.445	0.796	0.404
Global	Related	3	0.699	0.459	0.727	0.446

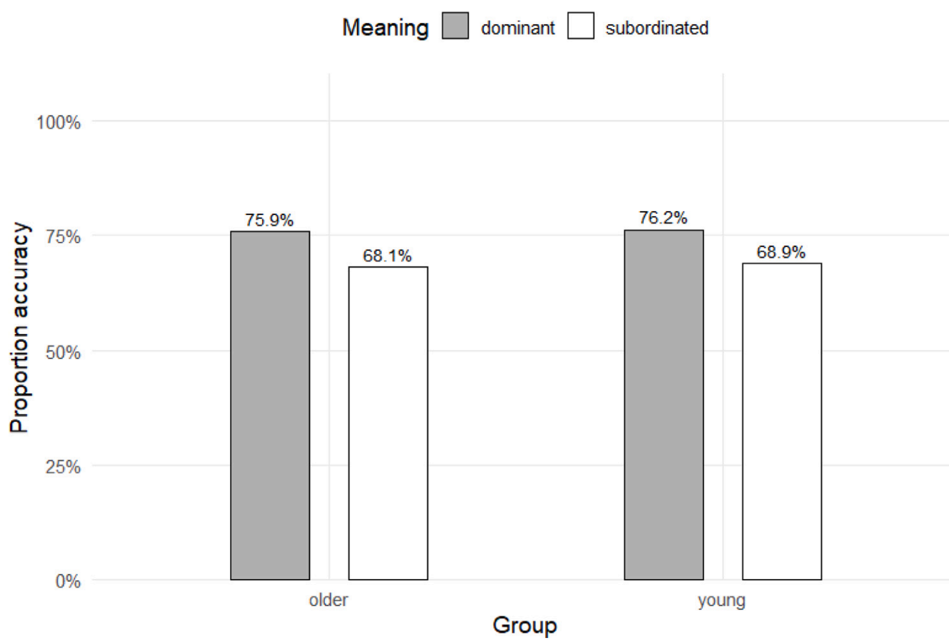

Fig. 4. Accuracy among groups in the condition of association on global meaning.

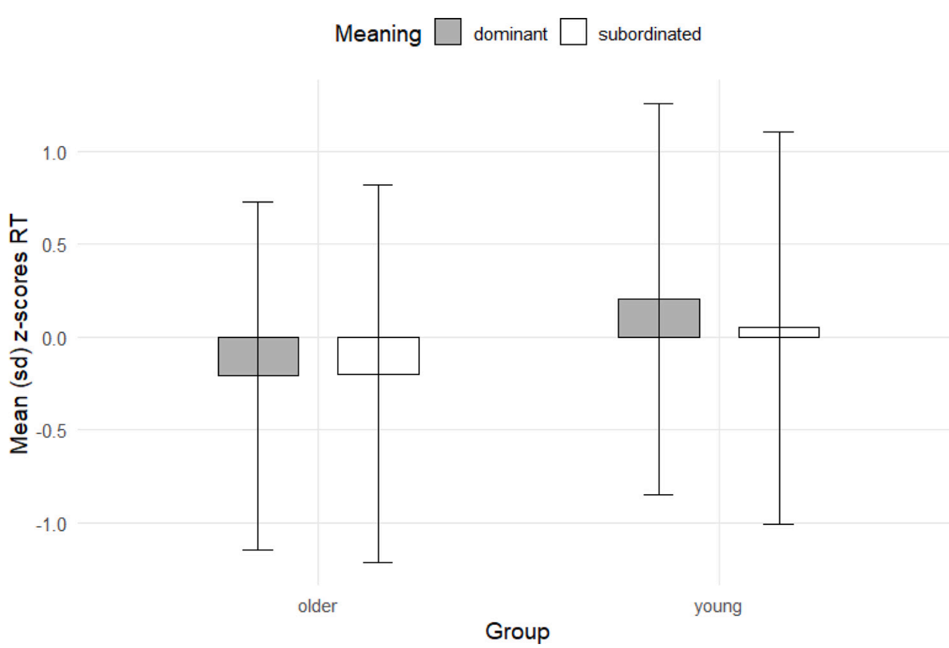

Fig. 5. Z scores of reaction time among groups in the condition of association on global meaning.

to selection. Interestingly, younger adults responded faster but made more errors under high selection demands.

These findings suggest that automatic processes like semantic activation and inhibition remain relatively intact with age, while confirming that executive control processes, particularly semantic selection, are more vulnerable to aging.

Moreover, correlation analyses between experimental indices and general executive measures (Stroop and fluency tasks) confirmed that semantic selection, rather than inhibition alone, was most strongly associated with executive performance, supporting the view that aging selectively affects interference control rather than semantic activation itself.

4.1. About activation and inhibition

In the priming task, response times were fastest when the prime was a monosemic word or an ambiguous word associated with its dominant meaning, and slowest when the prime was unrelated or associated with the subordinate meaning. These patterns were observed in both younger and older adults, suggesting preserved automatic semantic activation across age groups. Word-level facilitation for dominant over subordinate meanings was comparable across groups, reinforcing the idea that the underlying activation-inhibition dynamics remain present with age.

This interpretation is also supported by the methodological control that balanced ambiguous items between homonyms and polysemes, and the controlled monosemic condition to reduce ambiguity-structure confounds and supports attributing subordinated slowing to competition/inhibition.

These results align with the reordered access model of ambiguity resolution (Rodd, 2020; Rodd et al., 2012; Simpson & Krueger, 1991). Indeed, in a context-free setting such as ours, frequency effects dominate: the more frequent meaning of an ambiguous word is activated more rapidly and strongly than the less common one. For dominant meanings, this faster and stronger activation leads to a pronounced facilitation effect, slightly greater than that observed with monosemic words. In the case of subordinate meanings, the dominant meaning must be inhibited in order to access the subordinate one, which is also activated.

The interpretation of increased latency in the subordinate condition as reflecting inhibition is also consistent with the expectancy-based priming theory (Becker, 1980). The inhibition observed here likely reflects a later stage of inhibition, rather than early, automatic suppression. With a 1000 ms SOA, both prime and target are fully processed, allowing conscious access and the engagement of executive control mechanisms that inhibit internally activated but irrelevant meanings (Chein & Schneider, 2005; Copland et al., 2007; Holderbaum et al., 2019).

Therefore, the current findings suggest that late inhibition remains preserved with aging (earlier automatic inhibitory processes were not directly assessed with the present SOA). The priming results did not show a greater latency cost for subordinate meanings in older adults. This finding contrasts with Stroop task results, where older participants exhibited clear signs of impaired inhibition. One possible explanation is that generalized slowing in older adults alters the balance between activation and inhibition, reducing the observable contrast between dominant and subordinate meanings. This interpretation aligns with the model of Burke and Shafto (2004), who proposed that aging weakens the transmission of activation across semantic networks.

Alternatively, the apparent discrepancy may reflect the multidimensional nature of inhibition. While Stroop performance taps into domain-general interference control, priming tasks like ours may rely more on domain-specific inhibition, akin to negative priming, which has been shown to be relatively age-invariant (Gamboz et al., 2000; Hogge et al., 2008). In this framework, the increased latency in subordinate conditions reflects the cost of suppressing an automatically activated but contextually irrelevant meaning.

4.2. About selection and controlled retrieval

In the association task, all participants were more accurate when associating based on perceptual features (color, size) than when matching synonyms of ambiguous words, but this contrast was more pronounced in older adults. Notably, older adults maintained high accuracy in synonym conditions when distractors were absent, whereas performance dropped disproportionately in the presence of related distractors (*Group - Distractor* interaction), consistent with selective vulnerability to interference. This observation still support preserved controlled retrieval abilities and a broader semantic knowledge base (Verhaeghen, 2003).

Younger adults were more accurate overall than older adults, and showed faster responses specifically in the global association condition (*Group* × *Type of instruction* interaction). About this result, the larger difference between the feature and global conditions observed in younger participants seems to be actually a reflexion of the fact that older participants performed worse in the feature condition, but equally to younger participants in the global condition. This suggests that, in a condition of associating based on a single feature, older adults were more affected by the selection process induced by the global–feature contrast. Also, the greater vulnerability of older adults appears when semantic distractors are present (*Group* × *Distractor* interaction), indicating selective difficulty due to interference management rather than a generalized deficit.

However, performance in older adults declined markedly in the presence of semantic distractors, particularly in two conditions: when associating a subordinate synonym, and when selecting based on size. These patterns indicate that, while controlled retrieval remains largely intact with age, semantic selection becomes more vulnerable. This supports the notion that semantic selection involves two types of inhibition: early suppression of internally activated but contextually irrelevant meanings, and later-stage control over external distractors. Our findings suggest that aging is associated with a selective decline in executive processes related to interference resolution, rather than a domain-general executive decline (Gamboz et al., 2000; Hogge et al., 2008).

Consistently, both phonemic and semantic fluency correlated with global and feature-based association indices and with the proportion of dominant associations (Section 3.4), underscoring that selection efficiency under competition covaries with executive fluency skills, whereas no reliable link emerged with priming-based indices.

Taken together, these findings refine current theoretical models by showing that the effects of aging on semantic cognition are more selective than global. While late-stage semantic inhibition and controlled retrieval appear robust across age, selection processes, particularly under interference, are more vulnerable. This pattern supports the distinction proposed by Hogge et al. (2008) between internal inhibition and interference management, and aligns with the finding by Hoffman and Morcom (2018), that aging selectively impairs semantic selection but not controlled retrieval.

At the same time, our results challenge broader views that propose a generalized inhibitory decline in aging (Hascher & Zacks, 1988), by showing that some inhibitory mechanisms, such as those engaged in internal-information suppression, remain preserved. They also soften interpretations suggesting a decline in semantic activation (Burke & Shafto, 2004), pointing instead to a possible shift in the activation/inhibition balance rather than a degradation of the semantic network itself. Because the LDT used a 1000 ms SOA, our conclusions concern primarily *late* inhibition. Future work should vary SOA within-subjects to separate early vs. late inhibitory dynamics and test whether age affects these stages differentially.

Beyond these general age-related effects, future research should also explore whether the processing demands associated with feature-based associations differ according to the nature of the feature itself. Associations based on size is not processed equivalently. This pattern may reflect stronger engagement of controlled retrieval mechanisms for less salient or less automatically accessible attributes (e.g., size compared to color). Investigating this hypothesis could help determine whether semantic control resources are differentially recruited depending on the intrinsic salience and accessibility of the targeted feature, thereby refining our understanding of how controlled retrieval operates across varying types of semantic attributes.

By jointly assessing activation, inhibition, selection, and retrieval in the same individuals using original tasks in French, this study contributes to a more differentiated understanding of semantic control across the lifespan. It highlights the importance of moving beyond binary models of automatic vs. controlled processing while recognizing that the present design, centered on a 1000 ms SOA, primarily reflects late rather than early inhibition. Distinguishing these temporal components in future work will further clarify how early and late inhibition evolve with age. Neverthelsse, the data indicates preserved activation/inhibition and controlled retrieval with age, alongside a specific vulnerability of selection under interference that is behaviorally tied to executive fluency measures.

5. Limitations

This study combined two original tasks (LDT and CTTA) to assess semantic activation, inhibition, selection, and controlled retrieval using ambiguous words. While promising, this approach also presents some limitations.

A challenge in the CTTAT concerns age-related differences in verbal knowledge. The interpretation of subordinate meanings may vary across generations, independently of executive functioning; here, this factor was controlled by selecting ambiguous words based on normative data collected both from young adults (Thérouanne & Denhière, 2004) and from older participants (pilot pretest); nevertheless, this remains a variable that requires careful monitoring in such paradigms, as it can still influence results through subtle differences in semantic familiarity or vocabulary depth rather than cognitive processing per se.

Another limitation of the CTTAT lies in the complexity of the task design, which necessitated multiple conditions and constrained our ability to fully balance psycholinguistic variables (e.g., concreteness, frequency, length, imageability) across target words, cues, and distractors. Although the CTTAT showed robust age-related differences, future iterations could benefit from a refined item set where all selected items are equally comprehensible across age groups. This would ensure more uniform task difficulty and allow a clearer attribution of performance differences to cognitive processes, particularly when measuring effects through response time rather than accuracy alone.

Finally, our paradigm primarily captured inhibition occurring at a later stage in the LDT, due to the 1000 ms SOA. Early automatic inhibition, typically observable with shorter SOAs (<500 ms), was not directly measured. Future studies using the LDT could integrate additional priming conditions with shorter SOAs to dissociate these temporal components more precisely. Also, a fourth experimental block could be added to the CTTAT to independently assess these two inhibitory components within participants, thereby strengthening the specificity of the conclusions drawn.

6. Conclusion

In conclusion, this study examined how semantic activation, inhibition, selection, and controlled retrieval unfold across the adult lifespan. Using two complementary paradigms we jointly assessed both automatic and executive components of semantic control.

Our findings show that both younger and older adults benefited from semantic priming for dominant meanings and monosemic associates, while subordinate and unrelated pairs yielded slower responses. This pattern indicates that semantic activation and late-stage inhibition processes remain relatively stable with age, consistent with the interpretation of a preserved ability to suppress contextually irrelevant meanings at a controlled stage.

In contrast, selection was more sensitive to aging, as shown by older adults' increased difficulty when distractors were semantically related or when associations required focusing on a single feature. Nevertheless, controlled retrieval per se remained effective, suggesting that semantic knowledge breadth is preserved and that the main vulnerability lies in the executive component of selection.

Importantly, this interpretation was strengthened by controlling for potential lexical bias: ambiguous items were normed using data from both young adults (Thérouanne & Denhière, 2004) and older participants (pilot pretest). This ensured that age effects primarily reflected cognitive control mechanisms rather than differences in semantic familiarity. Yet, as noted, verbal knowledge remains a sensitive variable in this type of paradigm, and future studies should continue to refine normative control across generations.

Overall, the results support a differentiated view of semantic aging: rather than a global inhibitory decline, aging selectively affects interference management while sparing activation, late inhibition, and controlled retrieval. This multidimensional approach offers a more integrated understanding of semantic control across the lifespan and lays the groundwork for future investigations varying temporal parameters (e.g., SOA) to dissociate early versus late inhibitory dynamics.

CRediT authorship contribution statement

Sandra Invernizzi: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Sarah Gilis:** Writing – review & editing, Formal analysis. **Alice Bodart:** Writing – review & editing, Formal analysis. **Laurent Lefebvre:** Writing – review & editing, Supervision, Funding acquisition. **Isabelle Simoes Loureiro:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of ethic

The study received ethical approval from the central ethics committee of ULB Erasme Hospital (Belgium) and complied with the Declaration of Helsinki. Informed consent was obtained from all participants.

Declaration of Generative AI and AI-assisted technologies in the writing process

Various tools based on artificial intelligence (AI), including large language models, were used to assist in the structuring, formulation, and linguistic revision of the manuscript. These tools supported the authors in improving clarity, coherence, and readability of the text, but all conceptual content, data interpretation, and scientific conclusions were entirely developed, verified, and approved by the authors.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.actpsy.2026.106221.

Data availability

Data will be made available on request.

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