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Abstract

This study aimed to assess the effect of normal aging on the processing of taxonomic and thematic semantic relations.

We used the Visual-World-Paradigm coupled with eye-movement recording. We compared performance of healthy younger and older adults on a word-to-picture matching task in which participants had to identify each target among semantically related (taxonomic or thematic) and unrelated distractors.

Younger and older participants exhibited similar patterns of gaze fixations in the two semantic conditions. The effect of aging took the form of an overall reduction in sensitivity to semantic competitors, with no difference between the taxonomic and thematic conditions. Moreover, comparison of the proportions of fixations between the younger and older participants indicated that targets were identified equally quickly in both age groups. This was not the case when mouse-click reaction times were analyzed.

Findings argue in favor of nonspecific effects of normal aging on semantic processing that similarly affect taxonomic and thematic processing. There are important clinical implications, as pathological aging has been repeatedly shown to selectively affect either taxonomic or thematic relations. Measuring eye-movements in a semantic task is also an interesting approach in the elderly, as these seem to be less impacted by aging than other motor responses.

Keywords: normal aging; semantic processing; taxonomic relation; thematic relation; eye-movement recording

1. Introduction

A large body of work indicates that the organization of conceptual knowledge is shaped by two distinct types of relations between object concepts that are taxonomic and thematic semantic relations (Denney, 1975; Estes et al., 2011; Lin & Murphy, 2001; McRae et al., 1997; McRae et al., 2005; Medin & Ortony, 1989). Taxonomic and thematic relations refer to two different ways of semantically grouping objects (for a recent review, see Mirman et al., 2017), and their definitions have been relatively stable across studies. *Taxonomic relations* organize knowledge based on similarity and connect objects that share features, especially visuoperceptual ones (e.g., both ostriches and ducks have necks) (Kalénine et al., 2009). *Thematic relations* organize knowledge based on complementarity in events and connect objects that belong to the same spatial and/or temporal context (e.g., soap and a nail brush have complementary roles in the event of handwashing). Taxonomic and thematic relations have been shown to rely on at least partially distinct neural networks that may be independently affected by brain damage to anterior and posterior regions (de Zubicaray et al., 2013; Kalénine et al., 2009; Kalénine & Buxbaum, 2016; Lewis et al., 2015; Liu et al., 2019; Mirman & Graziano, 2012a; Schwartz et al., 2011; Xu et al., 2018). A selective deficit in the processing of taxonomic or thematic relations may thus be considered a sign of a pathological neural condition but also an avenue for compensatory rehabilitation strategies. However, it remains to determine whether the asymmetry in the identification of taxonomic and thematic relations is specific to pathological aging or whether it also affects normal aging.

A few studies have investigated the effect of normal aging on thematic and taxonomic processing, but most of them have employed explicit tasks. This raises several methodological problems, given the higher cognitive demands and potential contamination of semantic processing by extrasemantic processes (Merck et al., 2019; Ober, 2002). Using explicit matching or sorting tasks, Smiley and Brown (1979) and Annett (1959) found a preference for thematic over taxonomic relations in older (mean age 55 and 72 years, respectively) versus younger adults (mean age 27 and 20 years, respectively). These results were interpreted as reflecting the fact that thematic relations are more obvious and easier to recognize than taxonomic relations, as thematic relations are regarded as "a more natural way of organizing one's experience" (Denney, 1974, p. 49). For their part, Maintenant et al. (2011) demonstrated that compared to younger adults (mean age 28 years), older adults (mean age 70 years) exhibit a switching deficit when the task requires them to switch from thematic to taxonomic relations. These findings highlighted the lower cognitive cost of thematic processing and were in line with several behavioral and neurophysiological findings in young adults supporting the conclusion that thematic processing is faster, requires fewer cognitive resources, and is preferred over taxonomic processing (Kotz et al., 2002; Lawson et al., 2017; Lin & Murphy, 2001; Maguire et al., 2010; Sachs et al., 2008; Sass et al., 2009; Savic et al., 2017). At variance with this conclusion, Thompson et al. (2017) and Jefferies et al. (2020) have recently argued that semantic control (i.e., processes that allow task- and context-relevant aspects of knowledge to be brought to the fore, while irrelevant information is suppressed; Jefferies, 2013) is more intensely engaged in the case of weak rather than strong thematic relations. In their study, Thompson et al. (2017) administered an explicit picture-to-word matching task to patients with a semantic control deficit. In one condition, participants had to match a picture with a thematically related word. In another condition (*identity* condition), participants had to match a picture with the appropriate superordinate category label or a more specific name selected from among taxonomic distractors. Semantic strength varied within each condition. The authors found that patients with a semantic control deficit failed in both conditions, but were particularly impaired in the case of thematic relations with low semantic strength. According to the authors, this difference may have reflected a higher cognitive cost of retrieving the contextual information needed to identify weak thematic relations. The effect of semantic strength on semantic control appeared to be less evident in the *identity* condition. Taken together, most studies have reported that thematic processing requires lower cognitive demands than taxonomic processing, but without varying the effect of the strength of the relations. When weak versus strong relations were compared, Thompson et al. (2017) and Jefferies et al. (2020) showed that semantic control is more intensely engaged in the case of weak thematic relations, suggesting an important contribution of semantic strength to the effects observed. It should nevertheless be emphasized that the difference between relations in terms of semantic control remains subject to debate. Using a pupil dilation measure of semantic control, Geller et al. (2019) manipulated both the type (thematic vs. taxonomic) and strength of the semantic relation. They found that the semantic control requirement was mainly determined by the strength of the semantic relation, rather than the type. Given this result, it therefore appears crucial to carefully match items on semantic strength when comparing the two types of semantic relations. According to two recent studies by Hoffman (2018, 2019), matching relations on semantic strength is even more critical when they are to be assessed in the elderly. In the first study, Hoffman (2018) observed that older participants (mean age 77 years) performed more poorly than younger ones (mean age 19 years) on a task that required them to select an item with the same specific feature as the target if the distractor had a stronger semantic association with the target (e.g., "Which one is the same color as salt? Dove, pepper, cone or murder?"). In the second study comparing age groups equivalent to those of the previous study, Hoffman (2019) found that older participants' performance was predicted by an index of semantic control deficit, and not by an index of semantic deterioration. Hoffman concluded that, despite a broader and spared knowledge base, semantic control declines with age.

Together, previous research shows that the level of cognitive/semantic control needed to perform a task emerges as an important factor influencing explicit semantic performance in the elderly. As mentioned above, implicit tasks are useful for reducing the involvement of such intentional and controlled processes (Ober, 2002). In the present study, we chose the eye-tracking technique, which has been extensively used for more than a decade to implicitly investigate semantic knowledge in healthy participants, as well as in patients with stroke or neurodegenerative diseases (Bueno et al., 2019; Faria et al., 2018; Kalénine, Mirman, & Buxbaum, 2012; Kalénine, Mirman, Middleton, et al., 2012; Merck et al., 2020; Mirman & Graziano, 2012a; Mirman & Graziano, 2012b; Pluciennicka et al., 2016; Reilly et al., 2020; Ruotolo et al., 2019; Seckin et al., 2016; Xu et al., 2019; Yee et al., 2009). The protocol is based on the Visual World Paradigm, which involves a very simple word-to-picture matching task. Four objects are displayed on a computer monitor, and participants are instructed to locate a target picture corresponding to an auditory word. While they are doing so, their eye movements are recorded. The time course of gaze fixations on the different pictures in the display is assumed to reflect implicit semantic processing, in that distractor pictures that are semantically related to the target may compete for attention and be more fixated than semantically distant or unrelated pictures during the process of target identification. The protocol provides an implicit, fine-grained and - unlike other implicit approaches such as most priming paradigms - dynamic measure of semantic processing. Combined with a statistical approach allowing changes in gaze behavior to be analyzed over time, it has been successfully used to compare the amplitude and time course of taxonomic and thematic processing (Kalénine, Mirman, & Buxbaum, 2012; Kalénine, Mirman, Middleton, et al., 2012; Merck et al., 2020; Mirman & Graziano, 2012a; Mirman & Graziano, 2012b; Mirman & Magnuson, 2009). As time courses of gaze data involve multiple data point, the method is powerful, and allows to demonstrated differences in taxonomic and thematic processing even in small samples of participants (from 6-8 for patient groups to 15-20 for healthy participants, see Mirman et al., 2011; for equivalent sample sizes see also Kalénine, Mirman, & Buxbaum, 2012; Kalénine, Mirman, Middleton, et al., 2012; Lee et al., 2014 ; Merck et al., 2020; Mirman & Graziano, 2012a; Walenski et al., 2020). Moreover, it can highlight both reduced/delayed (reflecting impaired semantic activation) and increased/earlier (reflecting exaggerated semantic activation) semantic competition (Kalénine, Mirman, & Buxbaum, 2012). It could therefore be useful for detecting possible effects of aging on the processing of the two types of relation. With this method, Mirman & Graziano (2012b) have compared taxonomic and thematic processing in elderly participants (mean age 66 years), but participants' performance was not compared with that of younger participants. This study reported evidence for semantic competition with taxonomic and thematic distractors in older adults, with greater competition for taxonomic than thematic distractors. Recently, Merck et al. (2020) also used a similar paradigm to assess taxonomic and thematic processing in 15 healthy older controls and 9 patients with semantic dementia (SD), a neurodegenerative disease characterized by a gradual and selective loss of conceptual knowledge (Belliard et al., 2013; Bozeat et al., 2000 ; Gorno-Tempini et al., 2011; Landin-Romero et al., 2016; Neary et al., 1998; Snowden et al., 1989). Merck et al. (2020) reported different patterns of gaze fixations between patients with SD and older controls (mean age 68). While the two groups of participants were similarly sensitive to competition from taxonomically related pictures, patients with SD were far more sensitive than healthy controls to thematically related competitors before identifying the targets.

With the same experimental design, we here aimed at comparing the taxonomic and thematic processing between younger and older participants. Taking into account all the research described above, such experimental design ensures to a) use an implicit task associated with eye movement recording, to limit the involvement of controlled processes and obtain a fine-grained and dynamic measure of semantic processing, b) strictly match the strength of the semantic relations across taxonomic and thematic relations. Besides, considering the well-known cognitive slowing in the elderly (Salthouse et al., 1991, 1993, Salthouse, 1996) and the recommendation to take it into account when assessing the effect of aging on semantic knowledge with implicit tasks (Giffard et al., 2003; Lyons et al., 1995; Myerson et al., 1997; and to some extent, Moss et al., 1995), this experimental protocol also ensures to c) minimize the influence of cognitive slowing in the elderly by avoiding reliance on manual response times.

2. Materials and methods

The protocol was approved by the ethics committee of Lille University. The experiment was conducted in accordance with the Declaration of Helsinki (1964) and its later amendments (2013), and with current French legislation (Huriet Act, 1988). All participants gave their written informed consent before being included in the study.

2.1 Participants

We recruited 30 healthy adults, divided into two different age groups: 15 healthy younger adults (5 men, 10 women; mean age = 20 ± 2 years; range = 17-24) and 15 healthy older adults (5 men, 10 women; mean age = 68.5 ± 5.3 years; range = 58-77).

These sample sizes were established in view of the protocols applied in many other studies (Kalénine, Mirman, & Buxbaum, 2012; Kalénine, Mirman, Middleton, et al., 2012; Lee et al., 2014 ; Merck et al., 2020; Mirman et al., 2011; Mirman & Graziano, 2012a; Walenski et al., 2020) using both equivalent paradigm and statistical approach (see below for description). In addition, we ran a power analysis based on simulations from effect sizes and mixed-effect models reported in Merck et al. (2020) using the *mixedpower* R package (Kumle et al., 2021). Merck et al. (2020) also evaluated group differences (patients and controls) in the pattern of competition effects as the function of condition (i.e., interactions between group, object present in the display, and condition) with the same protocol. The power analysis confirmed that a sample of 30 participants is sufficient to reach 0.8 power for the detection of such interaction effect.

All participants were native French speakers. They underwent an extensive interview beforehand to ensure that they had no history of neurological or psychiatric disorders, or drug or alcohol use. Furthermore, older participants were only included after undergoing a short screening assessment to rule out any overall cognitive impairment (all scores on the Mattis Dementia Rating Scale [Mattis, 1976] were above the cut-off point [Pedraza et al., 2010]; mean score = 139.8 ± 2.81, range = 134-144) or lexical semantic disorder (all scores above the cut-offs on subtests of BECS-GRECO neuropsychological semantic battery [Merck et al., 2011]; mean picture-naming score = 38.67 ± 1.23, range = 36-40; mean verbal semantic matching score = 39.73 ± 0.59, range = 38-40; mean visual semantic matching score = 39.67 ± 0.62, range = 38-40; mean 6-item verbal semantic questionnaire score = 236.53 ± 1.81, range = 233-239).

In both age groups, participants were mostly right-handed (14/15 in the older group and 13/15 in the younger group).

Comparison of the groups on education level only showed a tendency to fewer years in the older group (mean education level = 11.7 ± 3.5 years, range = 7-20) than in the younger group (mean education level = 13.5 ± 1.5 years, range = 12-16), $t(28) = -1.898$, $p = .073$, 95% CI [-3.92, 0.19] (see Table 1 for the participants' demographic features). A difference of this nature is usually anticipated when comparing younger and older people, given the easier access to graduate studies for younger generations, and may not strictly reflect a difference in the level and quality of education per se (Le Rhun & Poulet-Coulibando, 2016).

2.2 Language assessment

To compare language abilities between the two age groups, we administered three tests: the synonym part of the Mill Hill Vocabulary Scale (MHV; Raven et al., 1998), the French adaptation of the National Adult Reading Test (fNART; Mackinnon & Mulligan, 2005) and the picture-naming task of the BECS-GRECO neuropsychological semantic battery (Merck et al., 2011).

2.3 Experimental materials and design

2.3.1 Stimuli

We used the same experimental task as in Merck et al. (2020). Stimuli were 468 color pictures of objects: 254 taken from Rossion and Pourtois (2004)'s object pictorial set, and 214 from OpenClipArt. These pictures were divided into five main sets: 26 target items (12 biological entities and 14 artifacts), 26 taxonomic competitors, 26 thematic competitors, 26 semantically unrelated but visually similar items (i.e., similar shape to the target, with the same orientation, dimension or color; visual similarity confirmed using the FSIM Toolbox; Zhang et al., 2011), and 364 semantically unrelated and visually nonsimilar items.

The task involved a total of 216 trials: 52 critical trials, 52 composed filler trials, and 112 unrelated filler trials. In each trial, four pictures were simultaneously displayed. In *critical trials*, the target was the reference object (e.g., *bell*) displayed with : 1) a competitor object that was either taxonomically (e.g., *whistle*) or thematically (e.g., *church*) associated with it, 2) an object that was semantically unrelated but visually similar to it (e.g., *knight's helmet*), and 3) an object that was semantically, visually and phonologically unrelated to both the target and the competitor and that differed between the thematic and taxonomic conditions (e.g., *raccoon* or *lobster*). The two other sets of trials were designed to avoid any anticipatory strategy, so that participants would not be able to guess which object was the target based on prior exposure. In the *composed filler trials,* the pictures used for the critical trials were rearranged so that either the taxonomic or thematic competitor became the target. *Unrelated filler trials* featured novel pictures that were unrelated to each other. In total, each target, taxonomic competitor, thematic competitor, and unrelated similar object appeared three times. Unrelated nonsimilar objects were displayed either twice (when they were selected as targets) or once (when they were never used as a target).

Concerning the presentation of the trials, two pseudorandomized orders were established, to avoid targets appearing in the same position twice or in consecutive trials. Targets that were first presented with their taxonomic competitor in Trial Order 1 were first presented with their thematic competitor in Trial Order 2, and vice versa. The two orders were counterbalanced across participants. Trials were divided into three fixed blocks, to allow participants to take short breaks.

Targets, taxonomic competitors, and thematic competitors were matched on several confounding variables (naming accuracy, naming latency, familiarity, age of acquisition, lexical frequency, name agreement, imagery agreement, or visual complexity) calculated from Rossion and Pourtois (2004)'s normative data and New et al. (2004)'s Lexique database (for all one-way analyses of variance: $F(2, 77)$, all ps > .125). The selection of taxonomic and thematic competitors was based on the definition of the two semantic relations used in Mirman and Graziano (2012a)'s study: "taxonomically related pairs were members of the same category and thematically related pairs frequently participated in an event or scenario and were not members of the same category" (p. 1991). These semantic relations were verified by independent raters. Taxonomic and thematic competitors did not differ on their semantic similarity to the targets, calculated using Latent Semantic Analysis databank (LSA), $t(25) = 0.231$, $p = .819$, 95% CI [-0.07, 0.08], as well as on the strength of their semantic relation to the targets, $t(25) = -0.712$, $p = .483$, 95% CI [-0.70, 0.34] (taxonomic: mean = 5.5 ± 0.7, range = 3.5–6.5; thematic: mean = 5.7 ± 0.9, range = 3.9-7). The procedure for assessing associative strength is described elsewhere (Merck et al., 2020). The strength of semantic relations between the targets and their competitors was measured in an additional group of 20 young adults (mean age = 25.6 ± 2.9 years, range = 20-31). Targets were presented with each distractor separately in pseudorandomized orders. Participants were instructed to rate the strength of the semantic association between each target and distractor on a 7-point scale ranging from 1 (*Not associated at all*) to 7 (*Very strongly associated*).

The four pictures (i.e., target, competitor, unrelated but visually similar, unrelated and visually nonsimilar) were also controlled on their relative visual saliency in each condition, using the Saliency Toolbox (Walther & Koch, 2006) (critical trials with taxonomic competitor: $\chi^2(9) = 5.54$, $p = .785$; critical trials with thematic competitor: $\chi^2(9) = 11.08$, $p = .271$), so that the low-level visual properties of the four types of pictures had the same potential to capture visual attention.

Finally, there were no significant differences in the distribution of the four types of objects in each corner of the screen / area of interest (AOI; see definition below in Subsection 2.4 "Data analysis") between conditions or pseudorandomized orders, (for all $\chi^2(9)$, all *p*s > .153).

The task also included a training session composed of eight representative trials featuring combinations of eight novel pictures, which made it possible to adjust the sound volume for each participant and make sure that the instructions were fully understood. This session could be repeated as many times as necessary for each participant.

2.3.2 Apparatus

A Tobii T60 eye tracker embedded in a 17-inch TFT monitor with a maximum resolution of 1280 x 1024 pixels was used to record gaze position and duration. Tobii Studio version 3.3.0 software (Stockholm, Sweden) was used for the recordings and the calibration process. The eye tracker has a 60-Hz sampling rate (every 16.67 ms) and a spatial resolution below 0.5°.

2.3.3 Procedure

Each participant was seated in front of the eye tracker, at a distance of approximately 60 cm. All the pictures were resized so that their width and height did not exceed 200 pixels. In each trial, four pictures were simultaneously displayed, with one in each of the four corners of the computer screen, so that they had a subtended visual angle of 8° (height) and 11° (width). Before starting the experiment, all participants underwent a five-point calibration. Once the calibration procedure has been validated, the eye-tracking recording could begin.

Participants were each informed that their eye movements would be recorded. They were instructed to look at the screen, and avoid moving their face and hiding their eyes. They did not receive any additional instructions about how to move their eyes, except during the calibration phase. The procedure was close to the one used in Kalénine, Mirman and Buxbaum (2012) and Kalénine, Mirman, Middleton, et al. (2012)non. Participants saw a central fixation cross (100 x 100 pixels) for 1000 ms, followed by a preview of the four-picture display lasting 1000 ms. A red circle (200 x 200 pixels) was displayed in the center of the screen for the last 250 ms of this preview, to draw participants' visual attention back to a neutral central location. This was followed by the word-to-picture matching phase, which lasted for 5000 ms, starting from the auditory word onset. Participants were instructed to click with the mouse on the picture that corresponded to the word they heard (Fig. 1). As in the passive version of Mirman and Graziano (2012b)'s study, trials had a fixed duration. However, instead of telling them simply to look at the target, participants were instructed to provide a click response, in order to assign a clear motor goal to the task. The fixed duration of each trial avoided eliminating trials from the gaze data analysis because of potentially clumsy clicks before word onset.

2.4 Data analysis

2.4.1 Mouse clicks

Accuracy was expressed as correct mouse clicks on the critical trials, which were recorded for each group (younger, older) and each condition (taxonomic, thematic). At a more qualitative level, we also recorded the nature of participants' errors: no response, confusion error with a competitor, confusion error with an unrelated picture, misclick (i.e., a clumsy click before word onset or outside of areas of interest defined for each picture).

Reaction times (RTs) were expressed in milliseconds and were only analyzed for correct responses on critical trials and after removing extreme RTs, namely those that were more than three standard deviations above or below each participant's mean RT. We thus excluded 5.38% of total trials for older participants, and 1.79% of total trials for younger participants. To ensure the normality of the distribution, RTs were log transformed. These log-transformed RTs were analyzed using linear mixed-effect models with group (younger, older) and condition (taxonomic, thematic) as fixed effects, and condition as a random slope for participants.

2.4.2 Fixation data averaging

We defined four areas of interest (AOIs), corresponding to 400 x 300 pixel quadrants in each corner of the computer screen. Fixations inside one of these AOIs were classified as object fixations, whereas fixations outside these AOIs were classified as nonobject fixations. For each 16-ms sample of a given trial, fixations could either be 1 (object fixations) or 0 (nonobject fixations). For each trial for each participant, the number of samples on each AOI was computed over 50-ms time bins. Sample data at the trial level was then averaged over trials, to provide an estimate of the time course of fixations on the target, competitor, and unrelated objects. Data from filler trials were excluded from the analysis. Only critical trials where the target image was correctly identified by the participant in both the taxonomic and thematic conditions were included in the gaze analysis. To minimize the impact of aging on ocular motility parameters (Seferlis et al., 2015), we compared the two age groups on the proportions of their fixations on the four objects, calculated for each time bin.

2.4.3 Growth curve analysis of fixation data

To test how aging impacts taxonomic and thematic semantic competition during object identification, we carried out a growth curve analysis, a multilevel modeling method that has proved useful for analyzing gaze data over time (Kalénine, Mirman, Middleton, et al., 2012; Mirman, 2014; Pluciennicka et al., 2016). The growth curve analysis allows simultaneous quantification of fine-grained time course differences between groups and/or conditions of interest as well as between individuals within a group or condition. This is particularly relevant for studies that aim at comparing small sample groups (Mirman et al., 2008).

At Level 1, changes in fixation proportions as a function of time were modeled using fourth-order orthogonal polynomials. The intercept term reflected the overall height of the fixation curve, the linear term reflected the slope of the curve, the quadratic term reflected the central inflection of the curve, and the cubic and quartic terms reflected inflections at the extremities of the curve. In brief, the intercept captured changes in semantic competition amplitude, whereas the other time terms captured changes in semantic competition timing. The effects of the factors of interest on the fixation curve were added as fixed effects to the model at Level 2. The random effect structure captured variations in the shape of the overall fixation curve between participants (random intercepts) and individual differences in the semantic competition effect (random slopes). The correlation between random intercepts and random slopes captures the extent to which individual manual response speed in related to the magnitude of the difference between taxonomic and thematic conditions. This might be useful when comparing groups with probable important differences in response times such as younger and older adults.

As for RTs, linear mixed-effect models of fixation data were fitted using lme4 (Version 1.1-21) and LmerTest (Version 3.1-0) packages in R (Version 3.5.1). Likelihood ratio tests (LRTs) for fixed effects were computed to provide an overall measure of the model's effect size, as well as an overall measure of model fit improvement after adding the factors of interest to the model. For linear mixed-effect models, significance *F* tests of fixed effects on each time term were calculated using the ANOVA function of the LmerTest package (Version 3.1-0). *P* values for *F* tests on fixed effects and *t* tests on parameter estimates of the model were calculated based on Satterthwaite's approximations. Post hoc paired comparisons (Tukey's adjustment) were also carried out, when relevant, using the emmeans package (Version 1.3.4).

Using the growth curve analysis approach, two sets of mixed-effect models were conducted on the gaze data during word-to-picture matching after target word onset:

a) *Analysis of fixations on the target object as a function of group and condition*.

This model served to compare target identification fixation curves between groups and conditions once the target word had been delivered. This additional assessment of target identification performance was assumed to be less contaminated by general slowing with age. Fixed effects of the model at Level 2 corresponded to group (younger, older), condition (taxonomic, thematic), and the interaction between the two. In particular, we wanted to evaluate the Group x Condition interaction on the linear term, as this would indicate variations in the slope of target identification between groups and conditions (see Lee et al., 2013, for a similar evaluation).

b) *Analysis of fixations on the distractor objects as a function of group and condition: assessment of semantic competition effects*.

The full model[1] serve to verify whether semantic competition effects were modulated by group and condition. Fixed effects of the model at Level 2 corresponded to object relatedness (C for competitors, i.e., semantically related distractors; US for unrelated but visually similar distractors; and UN for unrelated nonsimilar distractors), condition (taxonomic, thematic), group (younger, older), and their interactions. Object relatedness did not involve the target, as semantic competition is classically evaluated by comparing fixation time courses of related versus unrelated distractors.

We evaluated the interactions between object relatedness, group, and condition on the intercept and time terms. The interaction between object relatedness and group reflected the general impact of age on semantic competition. The interaction between object relatedness, condition and group indicated whether the impact of age differed according to the two conditions (taxonomic and thematic).

[1] Lmer structure of Level 2 models tested in the taxonomic and thematic conditions: model < - lmer(fixation~(intercept+linear+quadratic+cubic+quartic) * (Group*Object*Condition) + (intercept+linear+quadratic+cubic+quartic|Participant) + (intercept+linear+quadratic+cubic+ quartic|Participant:Condition:Object).

3. Results

3.1 Language performance

Comparisons of language abilities between the two age groups revealed no differences in either naming performance (picture-naming task of the BECS-GRECO; $t(28) = -0.57$, $p = .574$, 95% CI [-1.23, 0.69]) or the reading of irregular words (fNART; $t(28) = 1.13$, $p = .267$, 95% CI [-1.57, 5.43]). The only significant difference emerged when we compared scores on the synonym part of the MHV, $t(28) = 2.27$, $p = .031$, 95% CI [0.35, 6.71], with elderly participants performing better than younger ones (see Table 1).

3.2 Mouse click data

3.2.1 Accuracy

No errors were made by the younger group. In the older group, seven errors were recorded: four in the taxonomic condition and three in the thematic condition (mean accuracy = 99.1 ± 1.76%; range = 94.23-100%). Regarding the nature of the errors, they were essentially misclicks (4/7). The remaining three errors consisted of one confusion with a semantic competitor (taxonomic condition), one confusion with an unrelated picture, and one nonresponse.

3.2.2 RTs

The linear mixed-effect model on log-transformed RTs (LRT: $\chi^2(3) = 18.00$, $p < .001$) revealed a significant main effect of group, $F(1, 28.13) = 17.33$, $p < .001$, as younger participants were faster (mean = 1486.77 ± 294.43 ms) than older participants (mean = 1768.1 ± 361.71 ms). Neither the main effect of condition, $F(1, 28.26) = 2.98$, $p = .095$, nor the Group x Condition interaction, $F(1, 28.26) = 0.12$, $p = .731$, reached significance (for details of RTs in each condition, see Table 2), after taking into account the correlation between overall RT estimates and estimates of the effect of condition at the individual level in the random effect structure of the model (r = -0.38).

3.3 Fixation data

Trials in which participants clicked on the incorrect picture were excluded from the fixation analysis. In addition, to keep the item sets strictly equivalent at the individual level between the thematic and taxonomic conditions, we only considered critical trials where the target was correctly identified by the participant in both conditions and after removing outliers RTs (i.e., 97.7% of younger participants' data and 98.4% of older participants' data). Analysis of gaze data after word onset was performed on a 1000-ms time window starting 100 ms after word onset (minimum time required to plan and execute a saccade driven by the auditory prompt). Importantly, the time window was identical for both groups and both conditions, and included the rise of target fixation curves to their asymptote.

Regarding the number of fixations, there was a main effect of group, as younger participants made more fixations than older ones, $F(1, 28) = 16.52$, $p < .0001$, $\eta^2_{partial} = 0.371$ (see Table 2). Importantly, there was no main effect of condition, $F(1, 28) = 0.92$, $p = .346$, $\eta^2_{partial} = 0.032$, and no Group x Condition interaction, $F(1, 28) = 2.60$, $p = .118$, $\eta^2_{partial} = 0.085$.

3.3.1 Target identification after word onset

Adding the different fixed effects to the Level 1 model of target fixations after word onset did not improve the model's overall fit to the data (LRT: $\chi^2(15) = 15.51$, $p = .416$). *F* tests of fixed effects on the intercept term revealed no main effect of group, $F(1, 28.02) = 0.79$, $p = .382$, no main effect of condition, $F(1, 28.63) = 1.90$, $p = .179$, and no significant Group x Condition interaction, $F(1, 28.63) = 0.34$, $p = .566$. Tests of fixed effects on the time terms (linear, quadratic, cubic, quartic) did not reveal any difference in the shape of the curve for target fixations between groups and conditions (all *p*s > .11; see Table 3). Thus, there were no differences between younger and older participants in their visual identification of the target, be it in the amount or dynamics of fixations. Figure 2 depicts the overlap of the slopes of the two age groups, in both the taxonomic and thematic conditions.

3.3.2 *Semantic competition effects after word onset*

Adding the different fixed effects to the Level 1 model of distractor fixations after word onset improved the model's overall fit to the data (LRT: $\chi^2(55) = 118$, $p = .001$). F tests of fixed effects on the intercept term showed no main effect of group, $F(1, 28.24) = 0.58$, $p = .453$, no main effect of condition, $F(1, 142.25) = 2.28$, $p = .133$, and no significant Group x Condition interaction, $F(1, 142.25) = 1.05$, $p = .308$. However, the main effect of object relatedness was significant, $F(2, 142.25) = 6.16$, $p = .003$, as was the interaction between group and object relatedness, $F(2, 142.25) = 3.56$, $p = .031$. This significant interaction reflected a reduction in competition effects in the older group, regardless of condition. Results also revealed a significant Object Relatedness x Condition interaction, $F(2, 142.25) = 14.56$, $p < .001$, indicating that the amplitude of competition effects differed between the thematic and taxonomic conditions. However, the three-way interaction between group, object relatedness and condition was not significant, $F(2, 142.25) = 0.31$, $p = .733$, suggesting that the different patterns of competition effects between conditions were similar across younger and older participants. Post hoc analyses indicated that taxonomic competitors received more fixations than unrelated nonsimilar distractors in both age groups (younger group: estimate C - UN = 0.059, SE = 0.01, $t = 5.22$, $p < .001$; older group: estimate C - UN = 0.031, SE = 0.01, $t = 2.72$, $p = .018$), whereas no advantage of semantic competitors over unrelated nonsimilar distractors was found in the thematic condition (younger group: estimate C - UN = -0.003, SE = 0.01, $t = -0.32$, $p = .944$; older group: estimate C - UN = -0.028, SE = 0.01, $t = -2.52$, $p = .031$). In the older group, unrelated nonsimilar distractors even received more fixations than thematic competitors. Interestingly, semantic competitors did not receive more fixations than unrelated but visually similar distractors in either group or condition (all *p*s > .11).

Moreover, F tests of fixed effects on the time terms did not show any difference in the time course of fixations between either groups or conditions (all *p*s > .19; see Table 3).

An illustration of the shape of the two competition effects in the younger and older participants is provided in Figure 3.

4. Discussion

The present study was designed to assess the effect of aging on taxonomic and thematic processing. We used an implicit semantic task associated with eye movement recording, to limit the intervention of intentional and controlled processes (Ober, 2002) that are known to be altered in the elderly and which therefore hamper the explicit assessment of taxonomic and thematic processing (Hoffman, 2018, 2019; Maintenant et al., 2011). When we compared the proportion of fixations on distractors displayed alongside the target, we found that younger and older participants had similar gaze patterns in the two semantic conditions. The only effect of aging was an overall reduction in sensitivity to semantic competitors, with no difference between taxonomic and thematic relations. This pattern contrasts with previous results in patients using this protocol showing important differences in semantic competition between groups and conditions even in limited samples of participants (Merck et al., 2020).

This main finding raises the question of whether this decreased sensitivity with age can be attributed to the overall general slowing observed in the elderly, as has been demonstrated in previous priming studies (Giffard et al., 2003; Lyons et al., 1995; Myerson et al., 1997; and to some extent, Moss et al., 1995). In our study, analysis of mouse click RTs confirmed that older participants had slower manual motor reactions than younger participants. They manually clicked on the target about 300 ms later than younger participants, in both the taxonomic and thematic conditions. The effect of aging is not limited to manual motor RTs, but also affects ocular motility (Seferlis et al., 2015), and our older group did indeed make fewer fixations overall than the younger group did. In the visual world paradigm, we were interested in the relative numbers of fixations on the different objects in the display, and therefore compared fixation proportions. Although this limited the influence of the absolute number of fixations on semantic competition effects, the latter are relatively transient in nature and one could argue that the smaller number of fixations by older participants may have reduced the probability of observing competitive fixations in this group. However, the pattern of fixations on the target was not consistent with this interpretation. We did not find any difference in target fixation curves between the two age groups in either condition. No dampening of these curves was found in the elderly. It would therefore be difficult to explain why the reduction in the number of fixations would only affect competition effects while sparing the identification of the target. Rather, the overall reduction in sensitivity to semantic competitors was probably a subtle effect of normal aging.

It should also be noted that semantic competition effects are known to be very sensitive to methodological details. This is especially true for thematic competition effects, which tend to be relatively small and transient in healthy adults. In Mirman and Graziano (2012b)'s study, elderly adults exhibited a taxonomic competition effect that was substantially greater than the thematic competition effect. In our study, the limited proportion of fixations on the thematic competitor was probably due to the presence of an unrelated but visually similar distractor that was included in the display to control for the effect of visual similarity. We can speculate that the presence of a visually similar distractor may have reduced the saliency of the thematic competitor for both age groups, to which was added the general reduction in semantic competition in the older group. Participants (regardless of age group) may have attended differently to object features, depending on the type of distractors in the display (see Ruotolo et al., 2019). The processing of thematic relations therefore seems particularly sensitive to methodological details in the visual world paradigm, and more generally in the paradigms chosen to investigate semantic knowledge. Early studies had demonstrated a thematic preference in the elderly using explicit semantic tasks (i.e., matching or sorting tasks; Annett, 1959; Smiley & Brown, 1979), where participants are asked to make a deliberate choice between taxonomic and thematic relations. This preference was attributed to the engagement of a strategic decision-making process, which is easier and more obvious for thematic relations than for taxonomic ones (Denney 1974). In our study, the use of an implicit task may also have contributed to the abolition of this preference. Nevertheless, it should emphasize that if visual attention was not particularly driven to thematic competitors during target identification, consistent with some reports of relatively small and transient thematic competition effects in healthy young adults, visual attention was even driven significantly away from these distractors in older participants. Hence older adults did exhibit a reduction of visual attention to semantic distractors in both taxonomic and thematic conditions.

While implicit tasks are supposed to limit the engagement of intentional and controlled processes, we cannot completely rule out the possibility that semantic control played a role in the present result pattern. The absence of specific effects of normal aging on semantic competition will continue to fuel the current debate about whether the influence of the strength of the semantic relation is dependent on the type of that semantic relation or not. As we saw in the Introduction, Thompson et al. (2017) and Jefferies et al. (2020) have argued that semantic control is more intensely engaged in the case of weak rather than strong thematic relations, with this difference being less obvious for other types of semantic relations. Hoffman (2018, 2019) showed that semantic control declines with age, despite a broader and spared knowledge base. According to these views, the decrease in sensitivity to semantic relations with age should be specific to thematic relations, especially in the case of weak relations. In our study, semantic relations were strong in both conditions (means around 5.5 on a 7-point scale for both taxonomic and thematic relations). When items in each condition were strictly matched according to the strength of the semantic relation, the older participants exhibited an overall reduction in sensitivity to semantic competitors, with no difference between taxonomic and thematic conditions. This suggests that the engagement of semantic control is mainly determined by the strength, rather than the type, of semantic relation (Geller et al., 2019).

In the present study, the absence of a difference in the effect of aging on the processing of the two types of semantic relations also sheds light on the nature of semantic deficits in the elderly. In previous studies that used the visual world paradigm coupled with eye movement recording to assess semantic processing in pathologies affecting semantic knowledge, substantial differences were reported in fixation patterns between taxonomic and thematic conditions. Mirman and Graziano (2012a) examined the processing of the two types of semantic relations in participants with aphasia, following anterior or posterior left-hemisphere strokes. The two groups exhibited equivalent semantic impairment, but different patterns of fixations. For participants with posterior lesions, the effects of thematic competition were reduced and delayed, whereas the effects of taxonomic competition were comparable to those observed in controls. For participants with anterior lesions, taxonomic competition effects were longer lasting, but thematic competition effects did not differ from controls. As mentioned above, Merck et al. (2020) demonstrated an overreliance on thematic knowledge in 9 patients with semantic dementia. In this disease, thematic knowledge was reported to have a particular status and to be more resistant to the massive semantic erosion observed in this pathology than taxonomic knowledge (Merck et al., 2019). The overreliance on thematic relations highlighted by the eye movement recordings was interpreted as a sign of semantic disequilibrium. The hypothesis of semantic disequilibrium, based on previous findings (Kalénine, Mirman, & Buxbaum, 2012; Merck et al., 2014), states that taxonomic and thematic semantic processes are normally held in balance. When one process is impaired (taxonomic processing in the case of semantic dementia), the spared process (thematic processing in the case of semantic dementia) takes over. In our older group, the absence of such overreliance on thematic relations and, more largely, the absence of a difference in the effect of aging on the two semantic processes indirectly argue against semantic storage loss in the elderly. In terms of clinical implications, differences in fixation patterns between the taxonomic and thematic conditions could be considered as a marker of semantic knowledge breakdown, and thus verified where such semantic impairment is suspected.

Given the lack of evidence for a semantic storage loss, could the performance of our older participants reflect semantic access deficits instead? As Mirman and Britt (2014) pointed out, this type of semantic disorder encompasses a range of manifestations, and it remains unclear whether it corresponds to a single syndrome or to multiple subtypes of disruption, affecting sensitivity to cueing, sensitivity to rate presentation, performance inconsistency, sensitivity to number and strength of competitors, or word frequency effects (Warrington & Cipolotti, 1996; Warrington & Shallice, 1979). Regarding our use of an implicit semantic task, we could only explore the nature of the semantic deficit by focusing on sensitivity to the number and strength of competitors. Access deficit is characterized by an exaggerated sensitivity to the semantic relatedness of competitors, and thus by poorer performance on semantic matching tasks when distractors are semantically unrelated. However, our older participants exhibited a reduction in sensitivity to semantic competitors. They were less sensitive to both taxonomic and thematic distractors than younger participants, and there was no difference between the two age groups on the time course of the visual identification of the target.

Another interesting finding is that the slowing effect of age clearly appeared when younger and older participants were compared on their RTs for mouse clicks on the target, but not when we compared the time course of their fixations on the target. Visual identification of the target was therefore equally quick in both age groups. This unexpected gap between RTs and visual target identification times may lead to recommendations in the choice of methods for future research on semantic processing in aging. Unlike primed lexical decision tasks that rely on motor mouse clicks, eye movement recordings may limit the impact of motor slowing on the performance of older participants.

One limitation of this study that could be pointed is the small sample in each age group. The sample size is similar to those used in previous studies with equivalent paradigm and statistical approach and supported by power analysis based on previous results. In the present protocol, sufficient power is reached with a limited number of participants, probably thanks to the abundant amount of data collected per participant (a total of 1040 measures were obtained per participant). However, we acknowledge that observed effect sizes might be inflated and that it would be ideal to verify the robustness of the present findings with greater sample size. We nonetheless believe that they could in any case serve as preliminary outcomes in order to test more massively younger and older adults on thematic and taxonomic processing, with more participants and/or a less technically demanding protocol.

In conclusion, our study using an implicit semantic task associated with eye movement recording found no differential effect of normal aging on taxonomic and thematic processing. Instead, it revealed an overall decrease in sensitivity to semantic competitors in the older group, compared with younger participants. Although substantial differences in fixation patterns between taxonomic and thematic conditions have previously been reported in patients with a genuine loss of semantic knowledge (Merck et al., 2020; Mirman & Graziano, 2012a), the nonspecific effects of normal aging on semantic processing argue against semantic storage loss in the elderly. In terms of clinical implications, this finding shows that the eye-tracking can yield a valid marker of semantic knowledge breakdown, through differences in fixation patterns between taxonomic and thematic conditions. Eye movement recording should also be recommended in the elderly, as we demonstrated that eye movements are less impacted by the effects of aging than mouse-click RTs.

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Declaration of interest statement

None

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Features and Tests	Younger participants (5 males, 10 females)		Older participants (5 males, 10 females)	
	Mean (standard deviation)	Range	Mean (standard deviation)	Range
Age in years	20 (2) *	17-24*	68.5 (5.3) *	58-77*
Education level in years	13.53 (1.51)	12-16	11.7 (3.5)	7-20
Naming task (BECS-GRECO) (/40)	38.93 (1.33)	35-40	38.67 (1.23)	36-40
MHV-synonym part (/44)	33.07 (4.43) *	25-42*	36.6 (4.07) *	30-43*
fNART (/40)	27 (4.57)	21-36	28.93 (4.79)	19-34

Table 1. Participants' general demographic and neuropsychological features.

Note. * Significant difference between younger and older participants; MHV: Mill Hill Vocabulary Scale; BECS-GRECO: GRECO neuropsychological semantic battery; fNART: French adaptation of the National Adult Reading Test.

Participants	Measures	Taxonomic condition	Thematic condition
		Mean (standard deviation)	Mean (standard deviation)
Younger participants	RT (ms)	1500.4 (291.84)	1473.14 (296.77)
	Fixations	11613.27 (2124.1)	11744.47 (2081.13)
Older participants	RT (ms)	1776.09 (357.02)	1760.11 (366.65)
	Fixations	8271.07 (2467.94)	8237.8 (2537.46)

Table 2. Fixations and reaction times in the taxonomic and thematic conditions.

Note. Reaction times (RTs) are expressed in milliseconds and were calculated by averaging RTs for correct mouse clicks, after removing outliers. Fixations corresponded to the overall fixations per condition.

Fixation data after word onset	Main effects and interactions	Time terms				
		Intercept	Linear	Quadratic	Cubic	Quartic
Target identification	Group	*F*(1, 28.02) = 0.79, *p* = .38	*F*(1, 28.75) = 0.01, *p* = .97	*F*(1, 28.00) = 0.99, *p* = .33	*F*(1, 29.10) < 0.01, *p* = .92	*F*(1, 29.46) = 1.06, *p* = .31
	Condition	*F*(1, 28.63) = 1.90, *p* = .18	*F*(1, 34.41) = 2.20, *p* = .15	*F*(1, 28.00) = 0.20, *p* = .66	*F*(1, 32.34) = 1.82, *p* = .19	*F*(1, 36.25) = 1.31, *p* = .26
	Group x Condition	*F*(1, 28.63) = 0.34, *p* = .57	*F*(1, 34.41) = 0.57, *p* = .45	*F*(1, 28.00) = 2.69, *p* = .11	*F*(1, 32.34) = 0.21, *p* = .65	*F*(1, 36.25) < 0.01, *p* = .97
Semantic competition	Group	*F*(1, 28.24) = 0.58, *p* = .45	*F*(1, 28.08) = 1.045, *p* = .32	*F*(1, 33.23) = 0.06, *p* = .80	*F*(1, 40.52) = 1.31, *p* = .26	*F*(1, 35.42) = 0.04, *p* = .85
	Object	***F*(2, 142.25) = 6.16, *p* < .01**	*F*(2 142.08) = 1.67, *p* = .19	*F*(2 149.57) = 0.80, *p* = .45	*F*(2, 164.16) = 1.34, *p* = .26	*F*(2, 149.31) = 0.25, *p* = .78
	Condition	*F*(1, 142.25) = 2.28, *p* = .13	*F*(1, 142.08) = 0.07, *p* = .79	*F*(1, 149.57) = 0.26, *p* = .61	*F*(1, 164.16) = 0.48, *p* = .49	*F*(1, 149.31) = 0.07, *p* = .79
	Group x Object	***F*(2, 142.25) = 3.56, *p* = .03**	*F*(2, 142.08) = 0.67, *p* = .51	*F*(2, 149.57) = 0.37, *p* = .69	*F*(2, 164.16) = 0.85, *p* = .43	*F*(2, 149.31) = 0.40, *p* = .67
	Group x Condition	*F*(1, 142.25) = 1.05, *p* = .31	*F*(1, 142.08) < 0.01, *p* = .99	*F*(1, 149.57) = 1.13, *p* = .29	*F*(1, 164.16) = 0.76, *p* = .38	*F*(1, 149.31) = 0.08, *p* = .78
	Object x Condition	***F*(2, 142.25) = 14.56, *p* < .01**	*F*(2, 142.08) = 1.35, *p* = .26	*F*(2, 149.57) = 0.34, *p* = .71	*F*(2, 164.16) = 1.03, *p* = .36	*F*(2, 149.31) = 0.23, *p* = .80
	Group x Object x Condition	*F*(2, 142.25) = 0.31, *p* = .73	*F*(2, 142.08) = 0.53, *p* = .59	*F*(2, 149.57) = 0.81, *p* = .44	*F*(2, 164.16)= 1.14, *p* = .32	*F*(2, 149.31) =1.42, *p* = .25

Table 3. Full results of *F* tests on fixed effects of the model for target identification after word onset, and then for semantic competition effects after word onset.

Note. The main effects and interactions were evaluated on the different time terms describing the fixation curve (intercept, linear, quadratic, cubic, quartic). Values in bold indicate that the results are significant or tend to be significant.

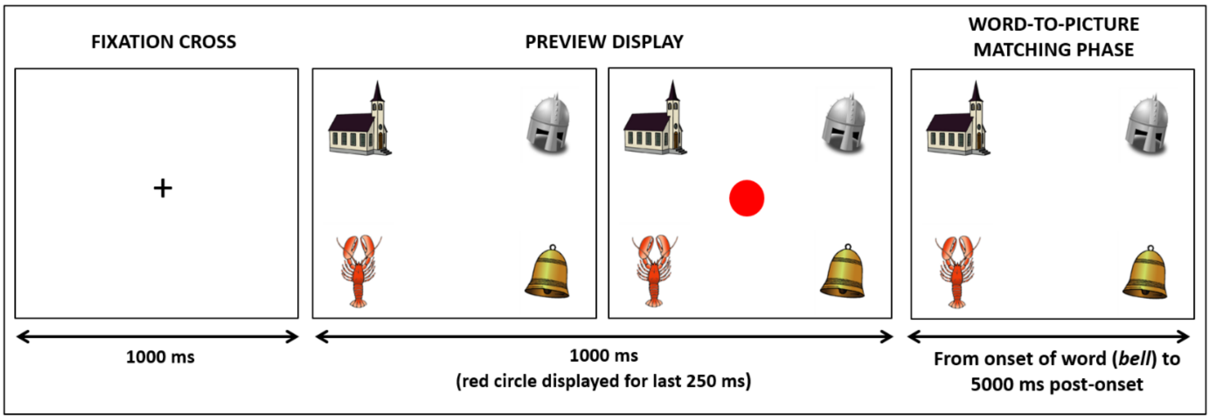

Figure 1. Illustration of procedure used for the eye movement recording. In this example of a trial, the target (*bell*) is displayed alongside a thematic competitor (*church*), a visually similar but semantically unrelated object (*knight's helmet*), and a visually dissimilar and semantically unrelated object (*lobster*). The target word was orally delivered after the preview display.

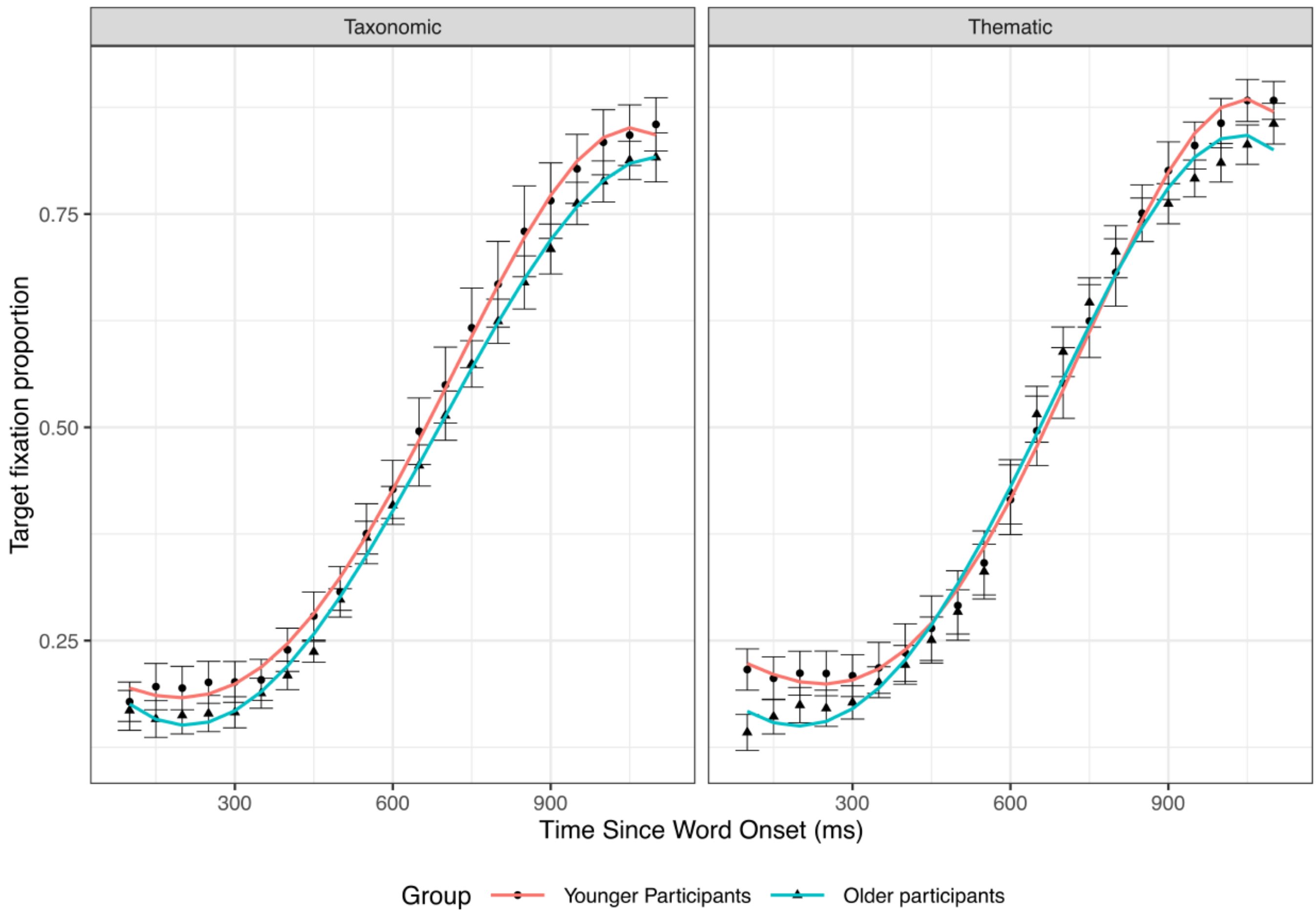

Figure 2. Model fit (lines) of fixation data (points) of the two age groups in the taxonomic and thematic conditions. Statistical tests did not reveal any significant difference in target fixation curves between the younger (orange line – black circles) and older (turquoise line – black triangles) participants, regardless of condition.

Error bars represent standard error of the mean.

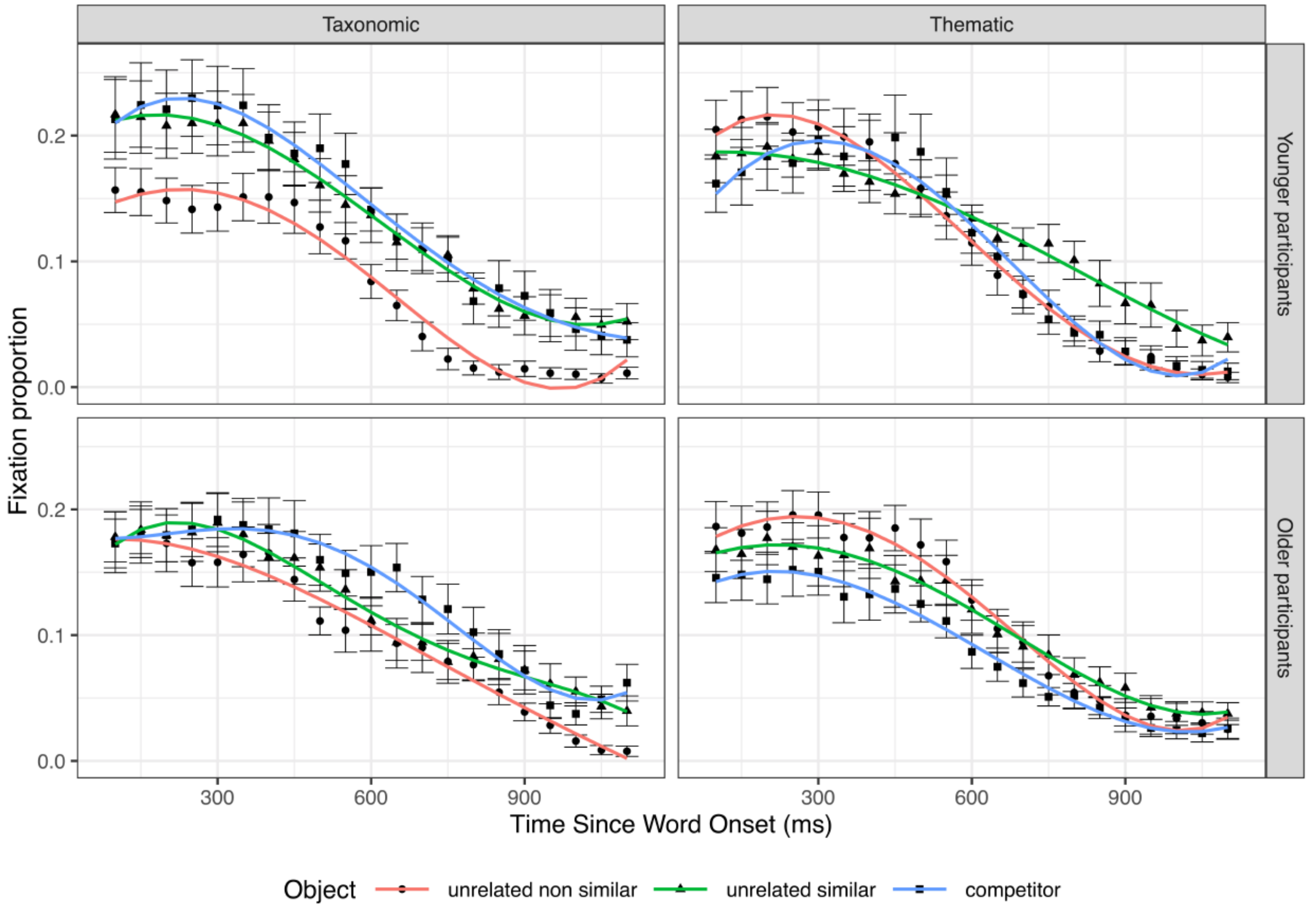

Figure 3. Model fit (lines) of fixation data (points) of the two age groups in the taxonomic and thematic conditions. In the older group compared to the younger group, statistical tests revealed an overall reduction in fixation proportions on the two semantic competitors (blue line – black squares), compared with the corresponding unrelated distractors (red line – black circles). The shapes of the competition curves were similar across the two age groups regardless of condition.

Error bars represent standard error of the mean.