Cognitive Processing
https://doi.org/10.1007/s10339-021-01024-7

RESEARCH ARTICLE

Using concept typicality to explore semantic representation and control in healthy ageing

Mara Alves[1] · **Patrícia Figueiredo**[2] · **Magda Sofia Roberto**[1] · **Ana Raposo**[1]

Received: 13 August 2020 / Accepted: 11 March 2021

Abstract

Successful use of conceptual knowledge entails the assembling of semantic representations and control processes to access the subsets of knowledge relevant in each situation. Research has suggested that representation and control mechanisms interact to support categorization. Notably, depleted representations in semantic dementia and disrupted control processes in semantic aphasia impair categorization of atypical concepts. Yet, it remains unclear how knowledge accumulation and control decay in healthy ageing impact categorization. To address this question, we compared young and older adults' performance in a categorization task of items varying in concept typicality. Critically, older adults were more accurate in categorizing atypical concepts than the younger counterparts, as indicated by the interaction between group and typicality. Moreover, the elderly outperformed the younger in categorizing atypical concepts that were also less familiar. Thus, the decay in semantic control observed along ageing did not significantly hinder the categorization of atypical items. Our data suggest that, relative to young adults, older adults possess enriched conceptual knowledge, which supports retrieval of the category-related features needed for categorizing atypical and less familiar exemplars.

Keywords Typicality · Categorization · Ageing · Semantic cognition

Introduction

Conceptual knowledge of objects and their features brings meaning to our experience of the world and is essential for many cognitive functions and behavioural skills. Recent research has proposed interactive semantic mechanisms that support the effective use of conceptual knowledge. In particular, semantic cognition requires *representation*, i.e. the capacity to assemble a multitude of information acquired throughout a lifetime of experiences, and *control*, i.e. the ability to strategically retrieve and select a subset of that knowledge to respond to the demands of the task at hand (Jefferies 2013; Lambon-Ralph 2014; Lambon-Ralph et al. 2017).

Age-related brain aetiologies are known to impair either semantic representation or control depending on the locus of the lesion (Jefferies and Lambon Ralph 2006; Marques and Charnallet 2013; Marques et al. 2013; Rogers et al. 2015). Yet, little is known about the dynamic interplay between these two mechanisms in healthy cognition, especially in late adulthood. Despite compelling evidences on the enrichment of semantic repositories throughout the lifespan (Hoffman 2018; Salthouse 2019; Verhaeghen 2003), less is known about how conceptual representations evolve as people grow older (Lambon-Ralph 2014), and whether the decline in cognitive control affects the adequate use of conceptual information (Hoffman 2018). The current study focuses on these open questions by exploring the effects of concept typicality in healthy ageing.

Handling editor: Markus Kiefer (University of Ulm); Reviewers: Antonio Calcagni (University of Padua), Paul Hoffman (University of Edinburgh).

✉ Mara Alves
mlalves@psicologia.ulisboa.pt

[1] Faculdade de Psicologia, Research Center for Psychological Science, Universidade de Lisboa, Alameda da Universidade, 1649-013 Lisboa, Portugal

[2] ISR-Lisboa/LARSyS and Department of Bioengineering, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

Published online: 29 April 2021

The representation of concept typicality along the lifespan

Typicality is a core element of conceptual representation. It refers to the graded membership of concepts into higher-order categories (Rosch 1975). For instance, while an olive is more atypical and a less representative member of fruit, an apple is more typical and a better exemplar of the category. Typicality has been explained by networks of overlapping features (Rosch and Mervis 1975) assembling concepts in distal or proximal positions within categories based on their similarities (Rogers and McClelland 2004). Measures of feature overlap have shown that atypical concepts not only share few features with their coordinate members (Rogers et al. 2015; Rosch and Mervis, 1975) and respective superordinate categories (Hampton 1979; Storms, De Boeck, and Ruts 2000), but also share many features with members of different categories (Rogers et al. 2015; Rosch and Mervis 1975). This pattern of feature sharedness renders atypical concepts as semantic structures of weak feature co-occurrence (Woollams 2012) and less related with other concepts (Rogers et al. 2015).

Effects of concept typicality are particularly pervasive in category-verification tasks. Participants take longer and are often less accurate in categorizing more atypical (e.g. deciding that an olive is a fruit) than typical items (e.g. deciding that an apple is a fruit; Hampton 1997, 1979; Kiran and Thompson 2003; Kiran et al. 2007; Sandberg et al. 2012; Räling et al. 2015, 2017; Räling et al. 2016; McCloskey and Glucksberg 1978; Rogers et al. 2015). Feature comparison is required in categorization decisions and assumed to take longer to reach the threshold of similarity to successfully include atypical concepts in the respective categories (Dry and Storms 2010; Hampton 1997). Failures identifying sufficient shared features between atypical concepts and their categories appear to underlie inaccurate decisions (Hampton 1997; McCloskey and Glucksberg 1979). The influence of typicality has been reported in other tasks beyond categorization, notably lexical decision (Hauk et al. 2006), picture naming (Holmes and Ellis 2006; Woollams 2012), and episodic memory tasks (Garcia-Marques et al. 2015; Greenberg and Bjorklund 1981; Schmidt 1996). This broad scope of typicality effects emphasises the critical role of feature similarity in cognitive functioning.

The representation of conceptual networks in memory is, however, a dynamic process (Barsalou 1982; Yee and Thompson-Schill 2016). It interacts with experience over time and is susceptible to factors determining acquisition and loss of knowledge (Barsalou 1982; Holmes and Ellis 2006; Rogers and McClelland 2004). Early studies suggested that people know less features of atypical than typical concepts, hence portraying atypical concepts as unfamiliar items with which they have few interactions (Aschraft 1978). However, this relationship is neither perfect nor unarguable (see Malt and Smith 1982; Rosch et al. 1976). Indeed, typical concepts tend to be familiar items, but atypical concepts can either be familiar or unfamiliar (Glass and Meany 1978; Holmes and Ellis 2006). Moreover, people do not necessarily have less knowledge about atypical items; instead they seem to know more about unique features rather than common features shared with other category members (Dry and Storms 2010; Malt and Smith 1982). Atypical concepts also tend to co-occur less frequently with their categories (e.g. olives are presented as fruit few times), while the category of typical concepts appears associated more often (Barsalou 1985; Casey 1992; Hampton 1997; Larochelle and Pineau 1994). Such reduced number of encounters has a negative impact on the richness of the representations, restricting opportunities to establish new connections and to reinforce existing ones (Barsalou 1983; Hampton 1997). Studies with healthy young adults have suggested that weak connections affect the retrieval of features, resulting in delayed but not hindered categorization decisions (Hampton 1997). Striking effects are then revealed in neurodegenerative diseases affecting the integrity of representations. In semantic dementia (SD), characterized by initial atrophy of anterior temporal lobes (ATL), patients present a clear loss of conceptual information, which follows a predictable pattern affecting primarily information less well integrated, namely more atypical concepts (Mayberry et al. 2011; Woollams et al. 2008) and more unique features (e.g. the hump of the camel; Bozeat et al. 2003; Hauk et al. 2007; Lambon-Ralph and Howard 2000). Together, these studies expose the vulnerability of atypical concepts, but also demonstrate that their representation is malleable and can be enriched through acquisition of knowledge and experience.

The potential growth of semantic networks has been well illustrated in computational models. In their simulations, Rogers and McClelland (2004), in addition to the successful replication of SD impairments, described adjacent transformations in the concept connections over the course of learning opportunities. Specifically, they have pinpointed that differentiation of concepts in the network capitalizes on both the number of times an item appears and the feature covariation provided by the coherent structure of typical concepts, such that additional training is needed until atypical items are associated with the category labels. Similarly, behavioural studies have shown that young people change their typicality ratings especially for atypical concepts after short intervals of time (e.g. one month) (McCloskey and Glucksberg 1978), training with pre-exposure improves performance of young adults in naming atypical concepts (Holmes

and Ellis 2006), and repeated presentation improves feature verification abilities for atypical items (Palma et al. 2018). It is thus reasonable to assume that a lifetime of experiences, ranging from acquisition of word definitions to actions learnt using objects, may build up more complex and detailed representations over time, which may favour atypical concepts by increasing the chances of going beyond salient and unique features to further apprehend other category features (e.g. olives are sour, caloric and eaten as appetizer but also grow in trees and have fleshy pulps enclosing the seed as other fruits).

Disruption of semantic control in pathological and healthy ageing

In addition to studying the dynamic representation of knowledge, researchers have used concept typicality to investigate the role of executive control in semantic cognition. Patients with semantic aphasia (SA), who present vascular lesions within the fronto-parieto-temporal language network, reveal preserved semantic repositories but impaired control processes to access their content. As first reported by Jefferies and Lambon-Ralph (2006), both SD and SA patients present difficulties in identifying semantic relations between concepts with weak co-occurrence, but for SA such difficulty occurred particularly when weak relationships (e.g. pliers-tweezers) were presented among irrelevant but strong associated competitors (e.g. lipstick, nail varnish, hairbrush). More recently, Rogers et al. (2015) found that both SD and SA participants performed worse than the healthy younger counterparts in the categorization of atypical concepts. Yet, in a naming task, while SD maintained exacerbated typicality effects, SA showed no difference in naming typical and atypical concepts. According to the authors, degraded representations make atypical concepts more confusable with members of different categories, leading to consistent impairments in categorization and naming abilities in SD. In contrast, because SA patients have disrupted control semantic abilities, naming typical items may place greater executive control demands than naming atypical objects, given the need to select the correct name among several competitors (e.g. a picture of cat activates similar concepts such as dog, tiger or lion). Contrariwise, in the categorization task SA patients may fail to inhibit different categories activated by atypical concepts, hindering decisions and leading to indistinguishable impairments between SA and SD.

Neuroimaging studies provide convergent findings on the interactive role of semantic representation and control in processing concept typicality in healthy cognition. In an fMRI study with young adults, Santi et al. (2016) revealed that categorizing more atypical items activated the ATL and the inferior frontal gyrus (IFG). As mentioned above, ATL is the brain region primarily affected in SD and has been referred to as multimodal hub distilling information across experiences to form coherent representations (Lambon-Ralph et al. 2017; Mayberry et al. 2011). It was also in this region that Woollams (2012) induced a temporary lesion using TMS to mimic SD naming deficits on atypical concepts in healthy young adults. The IFG, on other hand, has been associated with control processes of information selection, specifically in situations of great semantic competition (Thompson-Schill et al. 1997), as well as in the retrieval of weakly associated information (Badre and Wagner 2002). Of note, IFG is also activated during verification of less associated features of concepts (Raposo et al. 2012), an ability impaired in both SD and SA (Marques 2013). This provides strong evidence that semantic control in the IFG is critical during the categorization of atypical exemplars and in the verification of less associated features.

The need of cognitive control for regulating the use of conceptual knowledge casts doubts over the maintenance of semantic cognition in older ages. Notably, the natural cognitive decline in healthy ageing has been associated to disrupted control mechanisms, such as generalized slowdown in processing speed (Salthouse 1985, 1996), reduction of working memory capacity (Park et al. 1996; Park and Hedden 2001), and impaired ability to inhibit irrelevant information (Hasher and Zacks 1979; Hasher et al. 2007), which are known to affect processing efficiency and are often associated to neural changes in prefrontal regions. Decreasing cognitive control abilities have been proposed to explain the difficulties exhibited by older adults in studies tackling the use of conceptual knowledge. For instance, the ability to identify semantic relationships based on category membership (e.g. dog-elephant) or context co-occurrence (e.g. dog-bone) seems to be maintained from younger to older ages (Maintenant et al. 2011; Pennequin et al. 2006). However, as reported by Maintenant et al. (2011), older participants needed more trials than the younger to adapt when semantic relationships were switched. This suggests that older adults are capable of using conceptual knowledge in a successful manner, at least in situations with lenient control demands.

The capacity of older adults to uphold performance at the level of younger ages has been attributed to compensatory mechanisms, with neuroimaging evidence suggesting the crucial involvement of right prefrontal regions in regulating performance of high-performing older adults (Cabeza et al. 2002, 2018). However, the domain-general processes associated to right prefrontal regions may provide insufficient control resources in conditions that require semantic-specific control processes (Hoffman and Morcom 2018). Alternatively, it is possible that older adults may take advantage of their richer semantic repositories to compensate the decline of cognitive control. As showed by Hedden et al. (2005), vocabulary scores were more important in mediating performance in cued recall

for older than young adults. Indeed, older adults seem to have increased knowledge comparing to younger counterparts and better abilities to retrieve weak semantic relationships (Hoffman 2018). Striking difficulties for older participants arise with the need to inhibit irrelevant but strongly associated semantic knowledge (e.g. pepper) to select features linking weakly related concepts (e.g. salt-dove; Hoffman 2018). Interestingly, as showed by Hoffman (2019), while performance of young adults denoted unsophisticated knowledge, resembling SD behavioural patterns, older adults' difficulties in controlling semantic processes followed a tendency towards SA deficits. This suggests that difficulties in categorizing atypical concepts can be expected for both young and older adults, although driven by distinct mechanisms.

Evidence of lifelong typicality effects have been reported in studies investigating categorization in pathological and non-pathological ageing, notably in natural and artefact categories, which are well-represented in memory (Kiran et al. 2007; Kiran and Thompson 2003; Räling et al. 2016; Sandberg et al. 2012). In contrast, a reduction of typicality effects in healthy ageing was already noted in *ad-hoc* categories (e.g. things to take on a camping trip; Sandberg et al. 2012), which are ill-established in memory in younger ages (Barsalou 1983) and are more dependent of the appraisal of specific features (e.g. portability). The boost in categorizing atypical instances of *ad-hoc* categories in older ages suggests a refinement in retrieving detailed information, perhaps potentiated by enriched semantic repositories, despite the decay of inhibition and selection processes.

Current study

Convergent evidence points to the involvement of semantic representation and control in the processing of atypical concepts, with categorization decisions hindered either due to narrow semantic repositories or disrupted inhibition and selection processes. This study aims to investigate whether the development of richer representations upholds categorization of atypical concepts during ageing, offsetting weakened processing efficiency. We address this issue by comparing performance of young and older healthy adults in a semantic categorization task with items varying in concept typicality. If semantic representations can be enriched across learning experiences over time, then we expect that older adults with lenient control demands may retrieve more category related information than young adults, hence improving the successful categorization of atypical concepts. Alternatively, if the disruption of inhibition and selection processes affect categorization along ageing, then lenient control conditions may benefit young adults' categorization of atypical concepts relative to older adults.

Method

Participants

Thirty-two older adults (27 females), aged between 58 and 76 years old ($M = 65.9$, $SD = 4.6$), and nineteen young adults (16 females), aged between 21 and 29 years old ($M = 23.0$, $SD = 2.4$), participated in this study in exchange of a 20€ voucher. All participants had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. Elderly participants with no previous diagnosis of dementia or mild cognitive impairment, who volunteered to take part in this study, were recruited from senior universities in the Lisbon area. As such, we used a convenience sample, not representative of the elderly population at large; instead, the sample encompasses a well-educated segment of high functioning individuals. Cognitive decline was then screened by adopting a cut-off score below 22 points in the Montreal Cognitive Assessment (MoCA) test, following the Portuguese normative data (Freitas et al. 2012). One older participant was excluded based on this criterion. Young participants were recruited from public universities. The two groups were comparable in number of years of formal education completed (old: $M = 15.7$, $SD = 2.4$; young: $M = 15.0$, $SD = 0.85$). All participants gave written informed consent and received verbal information about the study procedure, as well as practice trials before the experiment. The study protocol was approved by the local ethics committee.

Materials and procedure

Cognitive assessment of older adults

Elderly participants were examined on a set of neuropsychological tests assessing global cognitive function and semantic abilities before carrying out the main semantic task. The MoCA test was used for screening of cognitive function (Freitas et al. 2010; Nasreddine et al. 2005). All participants included in the study scored 22/30 or above, all within the criterion of non-pathological ageing (cut-off: < 22) recommended for the Portuguese population (Freitas et al. 2012). Verbal semantic ability was assessed using the Vocabulary subtest of the Portuguese version of Wechsler Adult Intelligence Scale (WAIS; Wechsler, 1997), in which participants were asked to verbally define several concepts. Non-verbal semantic abilities were assessed using the picture version of the Camel and Cactus Test (CCT) adapted to the Portuguese language (Fonseca et al. 2016). Participants were required to select, among

four alternatives (one target and 3 distractors), the picture depicting the object sharing a semantic relation with the probe image. Answers were given through button-press. As proposed by Jefferies and Lambon-Ralph (2006), additional measures were obtained to qualify each trial of the CCT on three factors known to tap into distinct semantic mechanisms. Independent ratings acquired in a group of participants that did not take part in the main study ($n = 15$) were collected in a 7-point scale on (1) how easy it is to identify the relation between probe and target items (i.e. the understanding of the semantic relationship); (2) how often the two tend to co-occur in the same context (i.e. the strength of the relationship); and (3) how difficult it is to reject the distractors (i.e. the semantic competition exerted by foil items).

Semantic categorization task

Young and older participants performed the categorization task described in Santi et al. (2016). Ninety-six exemplars varying in typicality and selected from two natural kind (mammals and fruit) and two artefact categories (vehicles and clothing) were paired up with the respective category labels to form the "true" condition (e.g. mammal-whale). Another set of 96 exemplars selected from different categories were paired with the same category labels creating "false" trials (e.g. mammal-celery). Typicality values were collected in a 7-point scale (1 = very atypical to 7 = very typical). The selected exemplars ranged across the full scale of typicality. The familiarity of the exemplars, collected in a 7-point scale (1 = very unfamiliar to 7 = very familiar), was fairly distributed across the scale. The detailed procedure of ratings' collection can be found elsewhere (see Santi et al., 2016). Additional semantic measures were gathered from other sources. Age-of-acquisition (AoA) ratings in an 8-point scale (1 = learnt at the age of 0–2 to 7 = learnt at the age of 13 or older and 8 = learnt in adulthood) were retrieved from the normative study of (Marques et al. 2007). The items in the task covered different age bands of concept acquisition up to ten years old. Imageability ratings in a 7-point scale (1 = less imaginable to 7 = more imaginable) were obtained from MWP database (Soares et al. 2017). All exemplars scored high to very high in the imageability scale, as they are all concrete objects. Contextual diversity, a refined measure of word frequency, which considers the number of different contexts in which words appear, was taken from SUBTLEXPT (Soares et al. 2015). Items ranged in logarithmic scale from 0.00 to 3.71, with an average of 2.24. Descriptive statistics of all semantic measures are presented in Table 1 (see Fig.1 of Online Resource 1 for a graphical representation of distributions).

A procedure similar to Santi et al. (2016) was implemented, except that the probe and target were presented simultaneously and for a longer period to reduce the effects of memory capacity and computer agility, known to be diminished in older adults (Salthouse 1996; Park and Reuter-Lorenz 2009). Each trial began with a fixation cross presented for 500 ms in the centre of the screen, followed by the visual presentation of both the category name (e.g. mammal) and the target exemplar (e.g. whale) for 8000 ms. Trials were separated by a variable inter-trial interval (1500, 2000, 2500 and 3000 ms). Participants were instructed to decide whether the target exemplar presented in the bottom of the screen belonged to the category written above, using their right index and middle fingers for "yes" and "no" answers, respectively. They were encouraged to respond as accurately as possible using as much as needed of the time available. In half of the trials, the target belonged to the presented category (e.g. mammal-whale), while in the other half the target was from a different category (e.g. mammal-celery). The task was divided into three blocks, 64 trials in each, with block and item order randomized between participants. Presentation and timing of stimuli were controlled using EPrime software (http://www.psnet.com).

Statistical analysis

The analysis of the neuropsychological performance of older adults in CCT was conducted on response times (RTs) for correct responses to assess the influence of different semantic factors. We used a generalized linear mixed effect model with an inverse gaussian distribution. The model was specified by including three factors (Factor 1: easiness understanding semantic relationships; Factor 2: the strength of relationships; Factor 3: the competition of alternatives) as within-subject factors. This model included random intercepts for trials and participants. We used *p*-values based on asymptotic Wald tests to assess fixed effects

Table 1 Mean (standard-deviation), range and skewness (standard-error) of semantic characteristics of target exemplars across conditions in the semantic categorization task

	Typicality (1–7)	Familiarity (1–7)	AoA (1–8)	Imageability (1–7)	Contextual diversity (Log)
Mean (SD)	5.33 (1.35)	4.03 (1.16)	2.99 (1.01)	5.80 (0.46)	2.24 (0.61)
Range	1.75–7	2.03–6.66	1.30–5.48	4.44–6.75	0.00–3.71
Skewness (SE)	−0.83 (0.18)	0.46 (0.18)	0.52 (0.2)	−0.68 (0.19)	−0.53 (0.18)

significance. The semantic factors were standardized to avoid multicollinearity.

The analysis of the main semantic categorization data was performed on accuracy and RTs (for correct responses only). Trials with RTs below 300 ms were removed under the assumption of insufficient time to attend the stimuli. Items were considered outliers when accuracy was below 2.5 SD of average performance collapsing both groups. Nine (out of 192) items fell under this criterion (corresponding to 4.7% of the trials) and were thus excluded from the analyses. Mixed effects models were implemented to predict performance. First, we specified a model including group (older; young) as between-subject factor, and typicality and categorization condition (true; false) as within-subject factors. We were specifically interested in "true" trials as they present ideal conditions to test typicality effects (as target exemplars belong to probe categories). Generalized linear mixed effect models were implemented. To predict RT the inverse Gaussian distribution was used and to model accuracy the binomial one was applied. A random structure was constructed for each model according to the demands of the study. Each model included random intercepts for both participants and items, plus random slope for typicality varying within subjects. Fixed effects' significance was based on Wald tests. Other variables were considered for inclusion: schooling years of the participant, familiarity, AoA, imageability and contextual diversity of the exemplar. Continuous predictors were standardized to refrain multicollinearity issues. Deviation code was used for categorial predictors (Barr et al. 2013). To prevent overfitting, additional variables were only included if improved the model based on Akaike Information Criterion (AIC). Models convergence was assessed using default lme4 options, such as the nloptwrap optimizer, with parameters being estimated to increase precision. None of the models that included covariates demonstrated a better fit of the data, and hence we opted for the model without covariates.

These analyses were implemented using lme4 package in R (Bates, Mächler, Bolker, and Walker 2015). The ggplot2 package was used for graphical representation (Wickham 2016).

Results

Cognitive assessment of older adults

The average score on MoCA was 26.4, as shown in Table 2. Inspection of the different index scores in this test indicated well-preserved cognitive functions, although the lower memory index, loaded in episodic skills (Julayanont et al. 2014), suggests a decay of such abilities, known to decrease along ageing (Salthouse 2019; Park and Reuter-Lorenz 2009; Verhaegaen 2003). A detailed inspection of the individual scores revealed that a subgroup ($n = 16$) performed above age- and education-adjusted normative scores on MoCA. This suggests some variability in general cognitive function in our sample, with high-performance individuals exhibiting more efficient or optimal cognitive resources.

Table 2 Mean (standard-deviation), range and skewness (standard-error) of cognitive test scores for older participants

	Older adults ($n = 31$)		
	Mean (SD)	Range	Skewness (SE)
General cognitive function			
MoCA/30	26.41 (1.84)	22–29	−0.64 (0.42)
Executive/13	11.97 (1.05)	10–13	−0.68 (0.42)
Visuospatial/7	6.39 (0.80)	5–7	−0.84 (0.42)
Language/6	5.55 (0.68)	3–6	−1.92 (0.42)
Attention/18	17.45 (0.81)	15–18	−1.44 (0.42)
Memory/15	10.74 (3.47)	0–15	−1.23 (0.42)
Orientation/6	6.00 (0)	6–6	–
Semantic abilities			
Vocabulary WAIS/20	16.00 (2.30)	11–19	−0.51 (0.42)
CCT/64 (Semantic Association Test)	0.91 (0.04)	0.79–0.097	−0.95 (0.42)

All older adults performed above the standardized mean (10) in the Vocabulary test of the Portuguese version of Wechsler Adult Intelligence Scale (WAIS; Wechsler 1997), with a mean score of 16 ($SD = 2.3$; see Table 2). Average accuracy on CCT was 0.91 ($SD = 0.04$; see Table 2). The analysis on RTs ($M = 8.7$ s; $SD = 2.9$ s) was conducted at trial level with a generalized mixed effects model (see Table 3). Results showed a significant and positive effect of Factor 3 ($B = 3739.3$, $SE = 599$, $p < 0.001$), indicating that older adults had greater difficulty in selecting the target when distractors are harder to reject. We also found marginal negative effects of Factor 1 ($B = -1444.5$, $SE = 791.2$, $p = 0.068$) and Factor 2 ($B = -358.3$, $SE = 183.4$, $p = 0.051$), suggesting, respectively, a tendency for shorter RTs as the semantic relationship between probe and target items is easier to understand and as the co-occurrence of probe and target increases.

Semantic categorization task

Performance in the categorization task is shown in Fig. 1. The data were analysed using mixed effects models testing differences in age groups (between-subjects factor) in categorizing target exemplars varying in typicality (within-subjects factor) for "true" and "false" trials (within-subjects factor). The models successfully converged. Results for RT and accuracy data are shown in Table 4. Plots with predicted models are provided in Fig. 2 of Online Resource 1.

Table 3 Results of the generalized linear mixed effect model for RTs in the CCT

	RT		
	B (*SE*)	*t*	*p*
Fixed			
Factor 1	− 1444.5 (791.2)	− 1.83	0.069
Factor 2	− 358.3 (183.4)	− 1.10	0.051
Factor 3	3739.3 (599.2)	6.24	< 0.001
	σ^2		*SD*
Random			
Trial	0.000094		0.0097
Subject	0.00048		0.022

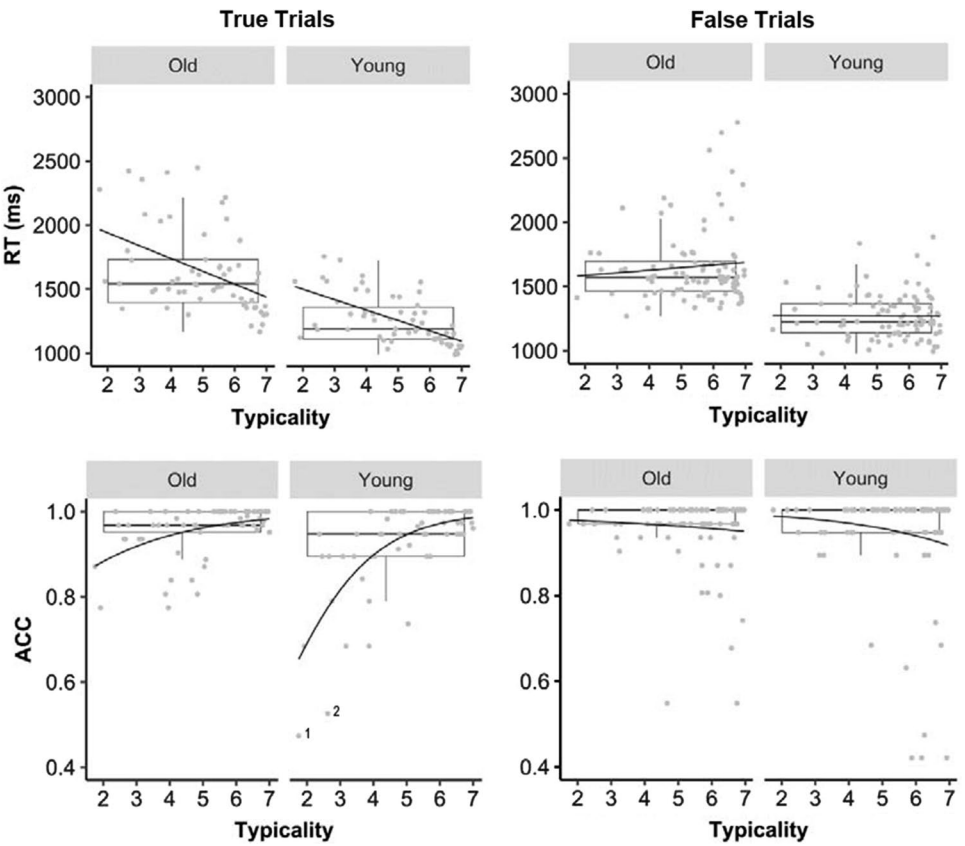

Fig. 1 Performance in the semantic categorization task: reaction times (RT, top) and accuracy (ACC, bottom), as a function of typicality, plotted separately by categorization trial (True/False trials, left/right columns) and group of age (Old/Young, left/right subplots). Circles represent performance for each typicality point, which may correspond to more than one target item. 1 = Vehicle-Lift, 2 = Fruit-Olive. The boxplots represent the median and the 25 and 75th percentiles. The trend lines represent the estimative of conditional means

Regarding RTs, there was a main effect of age group as older adults were significantly slower than young participants ($p < 0.001$). There was an effect of typicality, with increasing RTs as item typicality decreased ($p < 0.001$). There was also an effect of categorization condition with longer RTs for "false" than "true" trials ($p < 0.001$). Typicality interacted with categorization condition ($p = < 0.001$), as the longer RT for more atypical items were only observed in "true" trials, but not in "false" trials. No interaction between typicality and group ($p = 0.893$) and no three-way interaction between all factors ($p = 0.067$) were found.

Turning to accuracy, there were no significant differences between age groups ($p = 0.089$) and no effect of categorization condition, with similar accuracy for "true" and "false" items ($p = 0.474$). There was a main effect of typicality, with decreasing accuracy for more atypical items ($p = 0.002$). Similarly to what was found for RTs, there was no interaction between typicality and age group ($p = 0.633$), suggesting that the effect of typicality followed the same trend across groups. Also, consistently with the RTs data, we found a significant interaction between typicality and categorization condition ($p < 0.001$), with the typicality

Table 4 Estimates of fixed effects in the generalized linear mixed effect model for RTs and in the logistic mixed effect model for accuracy in the semantic categorization task

	RT			Accuracy		
	B (*SE*)	*t*	*p*	*B*(*SE*)	*z*	*p*
Fixed						
Group	−155.4 (35.6)	−4.36	< 0.001	−0.379 (.22)	−1.70	0.089
Typicality	−49.5 (10.9)	−4.51	< 0.001	0.437 (.14)	3.18	0.002
Typicality:Group	1.61 (11.9)	0.13	0.893	0.064 (.13)	0.48	0.633
True/False	78.5 (19.3)	4.06	< 0.001	0.190 (.27)	0.72	0.474
True/False:Group	−26.3 (16.3)	−1.61	0.107	0.047 (.26)	0.18	0.854
Typicality:True/False	104.5 (20.4)	5.13	< 0.001	−1.08 (.27)	−4.01	< 0.001
Typicality:True/False:Group	−31.8 (17.4)	−1.83	0.067	−0.709 (.24)	−2.90	0.004
	σ^2		*SD*	σ^2		*SD*
Random						
Item	13,726.1		117.2	1.92		1.39
Subject	13,975.1		118.2	0.38		0.62
Subject:Typicality	697.9		26.4	0.03		0.18

effect being restricted to the "true" condition. A three-way interaction was observed ($p = 0.004$). To further understand this effect, we analysed accuracy for "true" and "false" trials separately. For the "true" condition there was a significant typicality by group interaction ($B = 0.418$, $SE = 0.16$, $p = 0.008$), revealing that the typicality effect was larger for young than older participants. Of note, this effect emerged because older adults were better than young adults at categorizing atypical items: older adults revealed a smaller drop in accuracy with decreasing typicality (see Fig. 1 lower left-hand panel). In contrast, for "false" trials, no such effect was found ($B = -0.282$, $SE = 0.24$, $p = 0.237$).

An additional set of analyses was performed to compare young adults ($n = 19$) and a subgroup of older adults ($n = 16$), which included only participants performing above age- and education-adjusted scores in MoCA. This allowed examining performance of participants exhibiting optimal cognitive resources and to discard possible effects of disease onset (Cabeza et al. 2002, 2018). Young adults and optimal older adults had similar years of formal education (young: $M = 14.95$, $SD = 0.85$; old: $M = 15.94$, $SD = 2.14$; $t(18.9) = 1.74$, $p = 0.099$). In line with previous analyses, older adults were slower than young adults ("true trials": $B = -212.5$, $SE = 50.9$, $p < 0.001$; "false trials": $B = -261.8$, $SE = 45.8$, $p < 0.001$). The typicality effect was only significant in "true" ($B = -0.108$, $SE = 15.2$, $p < 0.001$), but not in "false trials" ($B = 18.5$, $SE = 17.5$, $p = 0.291$). In terms of accuracy, significant differences across groups were only found in "true" trials, with the optimal ageing group demonstrating more accurate responses than young adults ($B = -0.571$, $SE = 0.26$, $p = 0.028$). The typicality effect was also significant ($B = 0.747$, $SE = 0.14$, $p < 0.001$). These effects were qualified by a significant interaction ($B = 0.477$, $SE = 0.21$, $p = 0.021$), showing a smaller drop of accuracy in older relative to young adults as item typicality decreased.

Finally, to further explore changes in semantic processing, supporting the successful categorization of atypical exemplars from young to older ages, we conducted an additional analysis on a factor tracing knowledge breath, i.e. concept familiarity. As concept familiarity reflects the amount of experience with a given object (Lambon Ralph et al. 1998), if a richer semantic knowledge is responsible for older adults' improved performance on atypical items, then older adults should perform better than young adults on atypical concepts that are also less familiar. We split the sample of 96 target exemplars in "true" trials between typical ($M = 6.42$, $SD = 1.02$) and atypical items ($M = 4.18$, $SD = 0.066$; $t(58.29) = -13.34$, $p < 0.001$) based on median typicality. Following a similar procedure to Hoffman (2019), we identified 36 atypical items for which the groups of older and young adults differed in performance. Then, we computed the mean of item familiarity of the atypical exemplars better categorized by one group relative to the other and conducted a mean comparison test. Older participants outperformed young adults in atypical items that were also less familiar (older adults: $M = 3.49$, $SD = 0.88$; young adults: $M = 4.31$, $SD = 1.12$; $t(34) = -2.379$, $p = 0.023$; see Fig. 2). Of note, the subgroup of optimal ageing participants outperformed young participants in most trials.

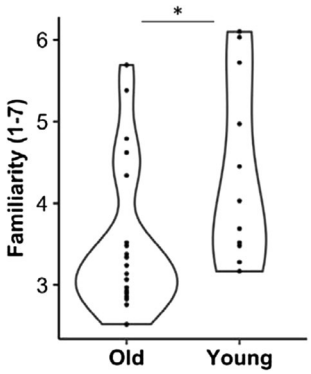

Fig. 2 Concept familiarity for atypical exemplars better categorized by old adults and by young adults. Violin plots represent the probability density of performance at different familiarity values. The asterisk indicates a significant difference between groups (*$p < 0.05$)

Discussion

This study aimed to investigate how cognitive changes along ageing influence the processing of concept typicality. We built upon previous evidence showing a dynamic interplay between semantic representation and control mechanisms regulating the processing of concepts less well integrated in the semantic network, as is the case of more atypical concepts. Given the contrastive ageing pattern of knowledge accumulation and decay of control functions, it was unclear if categorization of atypical concepts would be fostered or hindered from young to older ages.

Concept typicality effects in young and older adults

Typicality effects were found across age groups. More atypical concepts were consistently associated with longer and less accurate categorization decisions in young and older adults. Interestingly, however, a striking age-related difference emerged in the ability to successfully categorize concepts. Compared to young adults, older participants exhibited more accurate categorization responses of atypical items. This may result from the fact that adults in the later stages of life possess increased knowledge about concepts, which in turn may facilitate the correct inclusion of an atypical object in its semantic category (e.g. olive-fruit). This finding is in line with evidence of enlarged semantic repositories along the lifespan, which has been well documented in the psychometric literature, with systematic reports of increasing vocabulary scores from young to older ages (Park and Reuter-Lorenz 2009; Salthouse 2004, 2019; Verhaeghen 2003). The proposal that experience with concepts over time bolsters connections especially for more atypical items have been originally put forward by computational simulations (see Rogers and McClelland, 2004). Convergent behavioural evidence of enriched representations as a consequence of learning is found in reports of increased ratings of perceived concept typicality from infancy to early adulthood (Bjorklund, Thompson, and Ornstein 1983), as well as performance enhancement for atypical instances after repeated learning opportunities (Holmes and Ellis 2006) and training in verifying less associated category features in young adults (Palma 2018). Moreover, neuropsychological treatments that focus on the richness of atypical concepts have a greater impact in the recovery of age-related brain diseases, such as aphasia (Gilmore et al. 2020; Kiran and Johnson 2008; Kiran et al. 2011; Stanczak et al. 2006). Here we extend these findings and demonstrate that knowledge acquisition from early to late adulthood enhances the complexity of conceptual representations by fostering category feature knowledge for more atypical exemplars.

The age-advantage in categorizing atypical concepts occurred even when older participants exhibited signs of semantic control decay. Namely, longer RTs were observed in the CCT test when correct responses were selected among strongly associated alternatives, a pattern similar to that reported for SA patients, who presented difficulties in selecting the appropriate features while rejecting irrelevant ones (Jefferies and Lambon Ralph 2006). However, as reported by Hoffman (2018), despite the decay in inhibition and selection processes, older adults in situations without semantic competition constrains were better than younger adults in retrieving weakly related information. This ability was positively associated with knowledge breadth in both age groups, hence, suggesting that enriched semantic representations enhance retrieval (Hoffman 2018). Overall, these findings suggest that categorizing atypical concepts in healthy ageing may be facilitated by the ability to retrieve less associated features, supported by enriched knowledge about concepts, despite the decay of inhibition/selection processes. This is in line with the proposal that enlarged semantic repositories along the lifespan provide additional support to offset control decay (Hedden et al. 2005; Hoffman 2018). Moreover, when we restricted the analyses to the optimal ageing adults (as indexed by MoCA scores, to discard early effects of potential mild cognitive impairments), we observed an overall enhancement of categorization accuracy relative to young participants. This categorization boost clearly demonstrates the strengthening of semantic representations along healthy ageing. What contributes to such performance boost remains an important question for future studies. For instance, one can assume that adults in the optimal ageing group may have engaged in activities that simply strengthened their semantic repositories relative to older participants performing below age- and education-adjusted MoCA scores. In addition, it is plausible that the learning strategies engaged during active knowledge acquisition may have prompted the overall maintenance of cognitive resources, as has been reported in bilinguals (Berkes et al 2020; Bialystok et al. 2010; Luk

et al. 2011). Together, our findings concur to support that knowledge accumulation efforts increases cognitive reserve of individuals (Cabeza et al. 2018). Yet, it still is relevant to uncover the contribution of control processes and potential prefrontal compensatory mechanisms (Cabeza et al. 2002, 2018) in supporting the enhanced performance in categorization, particularly for atypical concepts in older ages.

Note, however, that the overall improvement in performance for optimal older relative to young adults did not obliterate the typicality effect, reiterating the relevance of this dimension in structuring semantic representations. The persistency of typicality effects across all age groups was also observed in RTs, with longer RTs for both young and older adults as typicality decreased. This suggests that feature comparison processes assumed to underly categorization decisions (Hampton 1997) continue supporting performance along ageing. However, older adults were overall slower than younger participants, despite similar accuracy. The overall increase in RTs is consistent with the well-known decay in processing speed in older ages (Salthouse 1985, 1996), which may be attributed to degraded white matter fibber paths, thought to be responsible for slowing down the exchange of information across the brain (Kennedy and Raz 2009).

The analyses exploring the effect of item familiarity on the categorization of atypical concepts support the pattern of increased knowledge in older ages. Consistent with the broadening of semantic repositories, older adults were more accurate than young adults in categorizing atypical concepts that were also less familiar. A similar pattern was also reported by Hoffman (2019), who showed that performance of young but not older adults was positively influenced by the familiarity of the targets. Interestingly, the trials in which young adults failed were the same in which SD exhibited poor performance (Hoffman 2019). This reveals that, in contrast to enriched semantic representations in late adulthood, unsophisticated semantic repositories in both young and SD patients (due to underdeveloped and depleted knowledge) are more sensitive to familiarity effects, which have been explained by differences in representation richness favouring more familiar items than less familiar ones (Funnell 1995; Lambon-Ralph et al. 1998; Hoffman 2019).

Caveats and future studies

Despite the utility of mixed effect models in experimental designs involving repeated measures (Barr et al. 2013), the estimation of parameters in complex random structures may compromise the quality of model convergence and its power. The models in the current study converged using default algorithms of lme4 package. However, in future studies it will be relevant to verify if specifying similar structures or maximal structures while applying different optimizers leads to convergent results. Also, our samples comprised highly educated young and older participants, who are not representative of the general population. Our findings indicate that the experience acquired over the lifespan provides opportunities to develop rich semantic representations, particularly for atypical and less familiar items. Such semantic enrichment may contribute to offset the effects of weakened controlled processes in older ages (Hedden et al. 2005; Hoffman 2018, 2019). Whether the same effects are observed in a more representative sample of older adults is an important question for future studies. In particular, it will be crucial to disentangle the effect of semantic knowledge accumulation from the effect associated with the number of years of schooling, which our study does not allow given the characteristics of the sample. Furthermore, despite the evidence of changes in semantic representation from young to older ages in our study, it remains an open question as to whether the age-advantage in categorizing atypical concepts would still be observed in situations constrained by control demands. Indeed, it can be argued that the categorization advantage should be observed not only in terms of accuracy but also in RTs. For instance, Hedden et al. (2005) showed that processing speed and vocabulary scores were positively associated in both young and older adults. In his study, Hoffman (2018) reported that, relative to young participants, older adults were more accurate in tasks testing knowledge breadth and, despite the overall slowdown, they matched young participants' RT specifically in these semantic tasks. Our results, however, showed an overall slowdown in the semantic performance from young to older ages and the increased accuracy in categorizing more atypical concepts in older ages were not associated with a reduction in RTs. In our categorization task, participants were presented with category and exemplars words simultaneously and were instructed to use as much as possible of the time available to answer. Such experimental conditions were introduced specifically to reduce generalized control demands inherently imposed in experimental settings either by the sequential presentation of the stimuli (e.g. Rälling et al. 2016; Santi et al. 2016) or restrictions in the time available to respond (e.g. 500 ms; Sandberg et al. 2012). Indeed, previous studies have shown that time pressure to answer impairs categorization decisions (Mack and Palmeri 2015; Rogers and Patterson 2007; Thorpe et al. 1996). With the imposition of deadlines to older adults (Rogers and Patterson 2007) and in ultra-rapid paradigms with young adults (Thorpe et al. 1996; Mack and Palmeri 2015), participants have exhibited an advantage in categorizing at the superordinate level (rather than basic level), which suggests that limited time constrains the retrieval of information only to coarse representations (Mack and Palmeri 2015). In our study, this would be particularly damaging to the processing of atypical exemplars, potentially hindering the access to category related features.

Conclusion

The typicality effect observed across age groups highlights the relevance of feature similarity as a mechanism of semantic representation, which seems to operate throughout the lifespan. This finding supports theoretical approaches to semantic knowledge based on the structural nature of concept typicality, in which concept cores are explained by networks of overlapping features capturing regularities across learning experiences (see Lambon-Ralph et al. 2017; for a discussion Dieciuc and Folstein 2019). Moreover, the observed categorization boost for more atypical concepts from young to older ages supports the view that semantic representations are strengthened along ageing. These findings reinforce the use of semantic variables, in particular concept typicality, for the treatment of semantic deficits (Kiran 2008) and deficits in other domains relatively anchored in semantic knowledge (e.g. episodic memory deficits; Kan et al. 2009).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10339-021-01024-7.

Acknowledgements We thank Andrea Santi for sharing the experimental stimuli and the senior students of UNISBEN for participating in this study

Funding This work was supported by FCT—Fundação para a Ciência e a Tecnologia (Foundation for Science and Technology of Portugal) through a PhD Studentship Reference PD/BD/114261/2016 to MA and a Project Grant Reference PTDC/PSI-PCO/118148/2010 to AR.

Availability of data and code Datasets supporting conclusions of this research article and the code customization described in text are available in Online Resource 2.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval The study procedure was approved by the Ethics Committee of Faculdade de Psicologia, Universidade de Lisboa.

Informed consent Informed consent was obtained from all participants in this study.

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