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Conceptual Knowledge Modulates the Temporal Dynamics of Novelty Preference for Real-world Objects in a Visual Paired Comparison Task

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Abstract

Our visual system tends to prioritise novel information, and this allocation of attention, as examined with the Visual Paired Comparison Task (VPC), is taken as an indirect index of memory processes. At present, research on the emergence of a novelty preference (NP) remains unclear about its temporal dynamics and agnostic about the role that the organisation of conceptual knowledge may play in it. These two gaps are addressed in this eye-tracking study, which adapts the VPC task to enable a finer temporal tracking of the NP while manipulating categorical and functional relationships between pairs of real-world visual objects to examine the impact conceptual associations bear on it. We found that NP significantly increases with increasing delay between the familiarisation and the test phase, especially for pairs of objects that were both categorically and functionally related (e.g., dart/dartboard). Our findings provide fresh evidence about the interplay between overt attention, conceptual knowledge and memory processes on novelty preference while offering valuable insights into the temporal dynamics of NP and its conceptual implications for mechanisms governing visual short-term memory.

Keywords: novelty preference; VPC task; recognition memory; eye movements; semantic knowledge; temporal dynamics.

Introduction

Overt attention is known to be captured by novel stimuli in the environment. This bias has been taken as an indirect measure of memory (i.e., Novelty Preference – NP, Chau et al., 2017; Eizenman et al., 2019). A powerful eye-tracking task to tap into these processes is the Visual Paired Comparison (VPC; Fagan, 1990), which assesses how much participants look at a novel stimulus compared to a familiar one when presented side-by-side. If the familiar object and the novel object are viewed for an equal amount of time, i.e., a 'null preference', it implies that the familiar object may have been forgotten (e.g., Ryan et al., 2007; Zola et al., 2000). Interestingly, as shown by Crutcher et al. (2009), this task can reveal memory degradation in dementia at an early stage (Mild Cognitive Impairment); individuals with MCI, compared to age-matched controls, display a significantly reduced NP after a 2-minute delay between the familiarisation and the novelty testing phases, suggestive of impairments in visual short-term memory. The diagnostic potential of the VPC task for signs of early dementia is corroborated in further research (e.g., Chau et al., 2015, 2017; Nie et al., 2020; Whitehead et al., 2018; Zola et al., 2013) and led to the development of machine learning classification models (Lagun et al., 2011).

Despite being a promising approach, this body of evidence remains agnostic about the temporal dynamics of the novelty preference effect. VPC has been used to compare only a short (2 seconds) with a long (2 minutes) delay between the familiarisation of the stimulus and its testing against a novel stimulus. However, the memory trace of the familiar object could progressively wane even over a short temporal window. Thus, it is critical to establish the temporal dynamics of NP to pinpoint a threshold more precisely at which recognition memory begins to fail.

Another gap in previous research is that the NP in the VPC has been tested using novel, abstract objects even though the conceptual organisation of knowledge could be important to the emergence of novelty. Visual objects have a semantic dimension describing how they are organised in the long-term knowledge system (e.g., a *fork* is conceptually related to a *knife* but not to a *ball*), which may influence the strength of memory encoding and, consequently, the capacity to recall them. Lists of semantically related words are, in fact, better remembered than unrelated ones (e.g., Kowialiewski & Majerus, 2020; Tse, 2009), and these findings extend to visual objects for which the strength of their conceptual associations positively correlate to visual working memory capacity (O'Donnell et al., 2018). Concepts can be organised based on their semantic category and functional properties (e.g., Luzzatti et al., 2020). For instance, a *knife* is *categorically related* to a *fork* because it belongs to the same semantic category (i.e., cutlery). However, it is also *functionally related* to *bread* because they are involved in the same action event (i.e., cutting a slice of bread) even though *knife* and *bread* belong to different semantic categories. The distinction between functional and categorical relatedness is critical in people with Alzheimer's Disease (AD) who display more significant impairment with the former compared with the latter (Johnson & Hermann, 1995). Since the association between concepts mediates memory encoding and may discriminate healthy ageing from neuropathological

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conditions, it becomes necessary to establish how functional and categorical relatedness would influence the temporal dynamics of novelty preference.

The current study

In the current study, we focused on two critical aspects of NP during a VPC task: (a) its temporal dynamics and (b) its dependence on the semantic organisation of conceptual knowledge. More specifically, we developed and tested a new version of the VPC task, in which we systematically varied the delay between the familiarisation and testing phase (from .6 seconds to 2 minutes) to track the development of an NP over time. The goal was to establish whether and how much the temporal delay would modulate the NP and thereby identify a hypothetical threshold after which recognition mechanisms start degrading. Second, we manipulated the types of conceptual relations among the objects to gauge their influence on the strength of NP. This second objective examined the relationship between conceptual knowledge and memory processes to reveal the semantic dimensions potentially contributing to the NP. We expect that objects encoded under stronger semantic associations (e.g., objects associated with both a categorical and a functional dimension) will be encoded more effectively in memory, thus leading to a more robust NP over time.

Method

Participants

Sixteen young adults (13 F; age = 26.56 ± 3.1 SD, 22-32 range) participated in the study. All participants had normal or corrected-to-normal vision and provided explicit written consent before participating. The study followed the 1964 Declaration of Helsinki and ethical procedures recommended by the Italian Psychological Association (AIP).

Stimuli

Nine hundred sixty colour images of single objects were sourced from the internet, using labels for categories that we found from existing databases (Brodeur et al., 2010, 2014; Hebart et al., 2019; Hovhannisyan et al., 2021; Moreno-Martínez & Montoro, 2012) to span a variety of established semantic categories. Only high-resolution pictures were selected by applying the option "large" in the Google size filter. Emotional stimuli, body parts, living (e.g., animals) and moving objects (e.g., means of transport) were not included because these features are known to impact memory processes (e.g., Chainay et al., 2012; Nairne et al., 2013). Half of the stimuli were used in the experimental pairs (n = 240) and shown during the familiarisation phase; the remaining half were used as novel objects during the testing phase of the VPC and the recognition phase (see Procedure for details). Experimental pairs were normed such that they could be grouped into one of four types of conceptual association: (1) functionally related objects from the same taxonomic category (*both*; e.g., dart/dartboard); (2) not functionally related objects but from the same taxonomic category (*categorical*; e.g., apricot/grape); (3) functionally related objects but not from the same taxonomic category (*functional*; e.g., nut/nutcracker); (4) objects from different taxonomic categories and not functionally related (*unrelated*; e.g., fire extinguisher/coconut; see Figure 1).

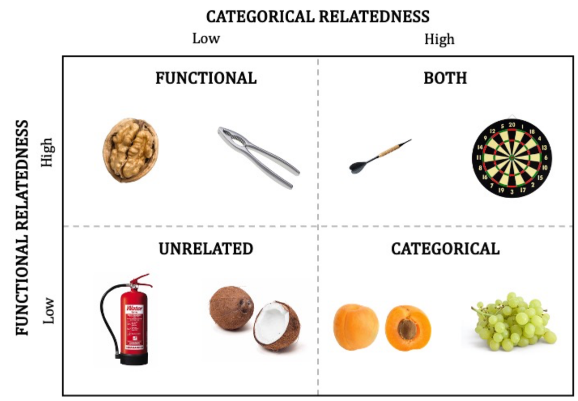

Figure 1: Example of experimental stimulus in the four conditions crossing categorical (low vs. high) and functional relatedness (low vs. high).

Norming data

20 Italian speakers (13 F, age = 29.95 ± 10.53 SD, 22-60 range) took part in a brief norming questionnaire administered in Qualtrics (Qualtrics et al., USA; https://www.qualtrics.com). Participants were asked, in the following order, to rate from 0 to 100: (a) the extent to which objects within each pair were related (*semantic relatedness*); (b) the extent to which they belonged to the same category (*categorical association*), and (c) the extent to which they could be used together to perform the same action (*functional association*). We had a total of 280 object pairs which were distributed into five lists, counterbalanced for the type of conceptual association, to ensure that the task could be completed within approximately 20 minutes. Each participant completed only one list containing 56 out of the 280 total pairs (i.e., 14 for each experimental condition). Ratings for *categorical* and *functional associations* were entered into a Supported Vector Machine (SVM) classifier to determine the most representative 240 pairs of the four association classes; then, a balanced K-means clustering algorithm was used to identify the 60 pairs for each type of association. We used the `e1071` and the `anticlust` R packages for these two analyses. Semantic relatedness scores were instead used to assess the overall strength of conceptual association between the objects in the pair, i.e., independently of their categorical and functional ratings. Pairs in the *both* condition showed the strongest semantic relatedness (M = 96.65%; SD = 3.29), followed by the *functional* (M = 83.2%; SD = 14.32), *categorical* (M = 79.62%; SD = 14.94), and *unrelated* (M = 4.93%; SD = 8.31) pairs. A one-way ANOVA further supported that pairs significantly differed in their semantic relatedness strength [$F_{(3,236)} = 809.7$, $p < 0.001$].

Apparatus

Participants sat 60 cm away from a 21-in. monitor (LCD DELL 1920 × 1080 px) with a refresh rate of 60 Hz. Each object in the pair was shown at a resolution of 500 × 500 pixels, which corresponds to 12.37° × 12.37° of visual angle, and placed an equal distance of 238.98 pixels, left and right, from the centre of the display (i.e., 6° of visual angle). Eye movements were recorded monocularly using an SR Research EyeLink 1000 desktop-mounted system at a sampling rate of 1000 Hz. A chin- and forehead rest was used to stabilize the participant's head. A nine-point calibration was run at the beginning of each session (x-axis = 0,14° of visual angle ± 0,14 SD; y-axis = 0,1° of visual angle ± 0,08 SD). The experiment was implemented on MATLAB (Version R2023b) using the Psychtoolbox extension (Version 3.0.19) (Brainard, 1997; Kleiner et al, 2007; Pelli, 1997).

Procedure

In previous versions of the VPC task, participants are first familiarized with two copies of the same object and then the familiarized object is presented alongside a novel object after 2 seconds or 2 minutes (the 'test phase'; Crutcher et al., 2009). Here, participants are familiarized instead with pairs made of two different objects, varying in their conceptual association (i.e., our experimental conditions) and then tested along a distribution of temporal delays spanning from 0.6 seconds to 2 minutes. In practice, each participant watched a sequence of 24 pairs of objects (i.e., 6 for each experimental condition) each pair presented for 2s with an Inter-Stimulus-Interval (ISI) of 0.6s. Then, they were tested, in reverse temporal order, with another sequence of 24 pairs, each comprising the familiarized object and a novel object (refer to Figure 2 for a schematic visualization). As we had 240 pairs, each participant completed 10 of such blocks. Drift correction was performed before each block. Participants were instructed to look at the pictures appearing on the screen (i.e., a free viewing). At the end of the VPC task, participants were told to perform a 2-Alternative Forced Choice (2AFC) surprise task, in which they had to select the object they had seen before by pressing either the left or the right arrow. To keep the timing of the entire experimental session manageable, each participant was asked to perform recognition on only half of the pairs presented in the VPC (i.e., 120 pairs, with 120 familiar objects, 30 for each experimental condition; and 120 novel objects). In both the VPC test phase and the recognition phase, the novel object was always unrelated to the familiar one, and the position of the two objects was counterbalanced to appear either in the same or in the opposite position compared to the familiarization phase. Each of the two familiar objects shown at familiarization was displayed either during the test or the recognition phase, resulting in two possible combinations equally distributed among participants. This means that between the test and the recognition phase and across all participants a total of 480 items, each representing a unique combination of two objects, were shown. Each participant completed a total of 360 trials (240 pairs in the VPC and 120 pairs in the 2AFC). The experiment was explained using written instructions and took about 30 minutes to complete (VPC ≈ 25 min; 2AFC ≈ 5 min).

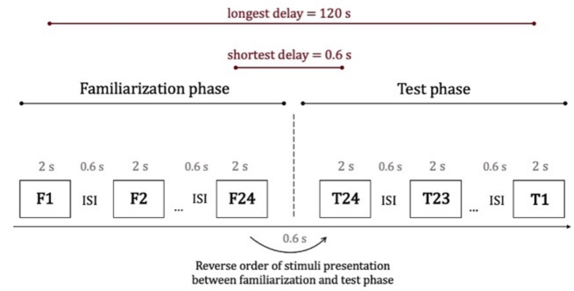

Figure 2: Schematic visualisation of a familiarization and test block in the VPC. Participants were familiarized with 24 pairs and tested in reverse order. The minimum and the maximum delays between the two phases were 0.6 s and 120 s with an Inter-Stimulus-Interval fixed at 0.6 s.

Data analysis

Analyses focused on data acquired during the test phase of the VPC and the recognition phase and were conducted on the R Statistical Software (Version 4.2.2, R Core Team, 2021) through the RStudio environment (Version 2022.12.0, RStudio Team, 2020). Fixation events were extracted from the raw gaze data using the SR Research Data Viewer software with default settings, which detects saccades based on velocity and acceleration thresholds of 30° s^{-1} and 9500° s^{-1} respectively. We excluded 2 (0.05 %) out of the 3,840 trials from the test phase (i.e., 16 participants × 240 pairs) that had less than 2 fixations, and 10 trials from one participant (0.52 %) out of the 1,920 trials of the recognition phase (i.e., 16 participants × 120 pairs) because of machine error. Thus, a total of 5,748 trials contributed to the analysis of which 3,838 trials were from the test phase and 1,910 trials from the recognition phase. Fixation data were first mapped to two rectangular Areas of Interest (AOIs) surrounding either the novel or the familiar object and then used to compute: (a) the *Novelty Preference Index* (NPI) in the test phase, which reflects the proportion of time participants spent looking at the novel object over the total amount of time viewing either object (and excluding viewing the blank screen) and (b) the *dwell time* which is the proportion of total viewing time spent looking at either the familiar or the novel object of successful recognition trials (N = 1,495). Finally, we also examined *response accuracy* in the recognition phase (a binomial, 1 for correct and 0 for incorrect responses). Statistical inference is obtained under the generalized linear mixed-effects models framework (G/LMM) as implemented in the `lme4` package in R (Bates et al., 2015). We predicted (a) NPI as a function of the *type of association* (four levels, *both* as the reference) and the *delay* (a continuous variable, 1-24, counting the number of intervening pairs between the familiarisation and the test phase); (b) recognition accuracy as a function of the *type of association* and the *NPI* at recognition (i.e., the preference of inspected a novel object over a familiar object), and (c) proportion of dwell time as a function of the *object* (familiar vs novel) and the *type of association*. Item (480) and participants (16) were evaluated as random effects. Models were first built with fixed effects as main effects and in interaction with random effects as intercepts only. Then, they were reduced backwards using the step function from the `lmerTest` package (Kuznetsova et al., 2017) to obtain the model with the most parsimonious number of parameters that best fitted the data (Matuschek et al., 2017). In the Tables, we report the coefficients of the predictors retained in the final model, their confidence intervals, which proxy the size of the estimated coefficients (Luke, 2017), and their t-values (or z-values for binomial outcome). The p-values are based on asymptotic Wald tests computed using the `lmerTest` package. Their significance level is reported in the table, next to the t/z-value, using asterisks (e.g., * = p < 0.05).

Results and Discussion

Test phase

We found that pairs belonging to the *both* condition generated a weaker NPI than any other type of association (refer to Figure 3A and Table 1). Moreover, NPI increased as the delay between the two phases also increased (Figure 3B), especially in the *both*, and to a lesser extent, the *functional* condition (Figure 3C). Possibly, if two objects have been categorically and functionally associated, more effort is required to update the memory representation when a novel object is introduced during the test phase. The increased attention towards the novel and unfamiliar object indicates an effort to substitute a conceptually related familiar one in the memory trace of the previously encoded association.

Recognition phase

Response accuracy was significantly modulated by the type of association, whereby performance was lower in the *both* condition compared to all other types of association, and by the NPI whereby better recognition occurred when participants showed a reduced novelty preference during the recognition phase (refer to Figure 4A and Table 1). For the proportion of dwell time during successful recognitions, familiar objects were looked at significantly more than novel objects. Fixating for longer on the familiar object indicates that it was better remembered by participants, who evaluated it to make sure it was the one they viewed before. This corroborates that a stronger NPI implies a significant decrement in response accuracy. Recognition accuracy was significantly lower in the *both* condition, and in fact, participants required a higher proportion of time on the familiar object to be successful compared to the *functional* and *categorical* conditions. Participants need to linger for longer on the familiar object in the *both* condition because objects were encoded under a strong conceptual association, which was disrupted for the first time when a novel object was introduced during the test phase, as speculated above, and now with a second novel object during the recognition phase. The continuous re-association of such familiar objects with unrelated novel objects has inevitably degraded its memory trace as a single object. This result indicates that differences in the type of association built between the objects directly mediate their mnemonic strength and consequently impact the deployment of overt attention.

Table 1: Generalized and linear mixed effects model outputs for Novelty Preference Index, Response Accuracy and Proportion of Dwell Time. Predictors entered in the G(L)MER were Type of Association (categorical, functional, unrelated, both, with both as reference level), delay (continuous variable, 1-24), NPI (continuous variable, 0-1) and object (familiar, novel, with novel as reference level). Participants (16) and Item (480) were the random effects introduced as intercepts.

Novelty Preference Index

Predictors	β	CI (2.5%; 97.5%)	t-value
(Intercept)	**0.47**	**0.45; 0.49**	**44.80*** **
categorical	**0.04**	**0.01; 0.07**	**2.65** **
functional	**0.03**	**0.003; 0.06**	**2.18* **
unrelated	**0.05**	**0.02; 0.08**	**3.32*** **
delay	**0.002**	**0.0003; 0.003**	**2.40* **
delay × categorical	**-0.002**	**-0.004; -0.0001**	**-2.04* **
delay × functional	-0.001	-0.003; 0.001	-1.27
delay × unrelated	**-0.003**	**-0.005; -0.001**	**-2.88** **

Response Accuracy

Predictors	β	CI (2.5%; 97.5%)	z-value
(Intercept)	**4.47**	**3.90; 5.1**	**-14.73*** **
categorical	**0.41**	**0.03; 0.8**	**2.09* **
functional	**0.74**	**0.36; 1.15**	**3.71*** **
unrelated	**0.41**	**0.03; 0.8**	**2.1* **
NPI	**-6.79**	**-7.78; -5.87**	**-13.99*** **

Proportion of Dwell Time

Predictors	β	CI (2.5%; 97.5%)	t-value
(Intercept)	**0.42**	**0.40; 0.43**	**50.89*** **
categorical	0.02	-0.005; 0.04	1.53
functional	**0.04**	**0.02; 0.06**	**3.4*** **
unrelated	0.01	-0.008; 0.04	1.29
object	**0.17**	**0.14; 0.19**	**14.43*** **
object × categorical	**-0.03**	**-0.06; -0.001**	**-2.03* **
object × functional	**-0.07**	**-0.1; -0.04**	**-4.19*** **
object × unrelated	-0.03	-0.06; 0.004	-1.69

Note: The final model formulas in Wilkson notation, resulting from stepwise backward selection, are:
a) Novelty Preference Index ~ type of association + delay + type of association:delay + (1 | item)
b) Response Accuracy ~ type of association + NPI + (1 | item) + (1 | participant)
c) Proportion of Dwell Time ~ type of association + object + type of association:object + (1 | item) + (1 | participant)
(*) p < .10, *p < 0.05, **p < .01, ***p < .001

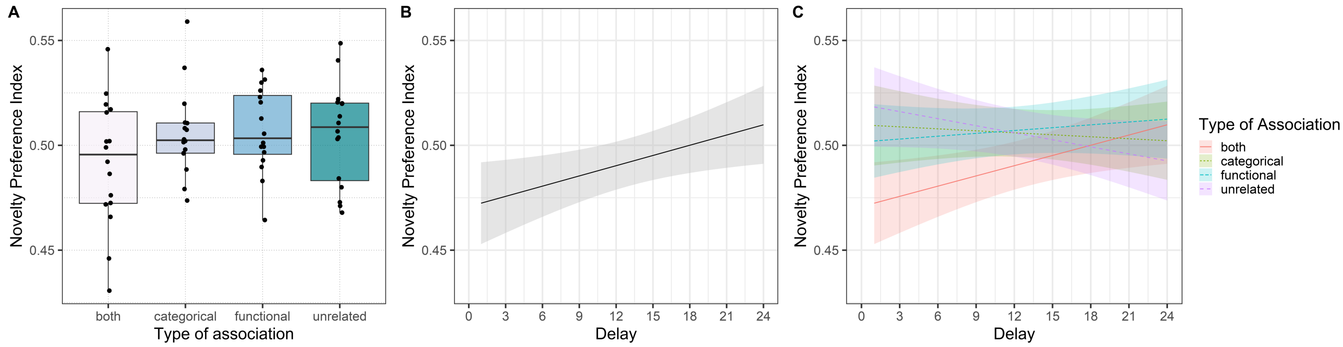

Figure 3: Novelty Preference Index during the test phase expressed as a proportion. (A) Box plot of the NPI as a function of the type of association. The hinges of the boxplots represent the 25th and 75th percentiles of the measure (lower and upper quartiles), while the horizontal line represents the median of the distribution. Each dot indicates the by-participant average for that measure. (B) Predicted values of NPI as a function of the delay. The solid black line represents the estimate of a linear mixed-effects model fit to the data. The grey shaded area represents the corresponding 95 % confidence band. (C) Predicted values of NPI as a function of the delay and type of association. The lines represent the linear mixed-effects model predicted fit for each type of association (red-solid = both; green-dotted = categorical; turquoise-dashed = functional; purple-long dash = unrelated). The shaded areas represent the corresponding 95 % confidence band.

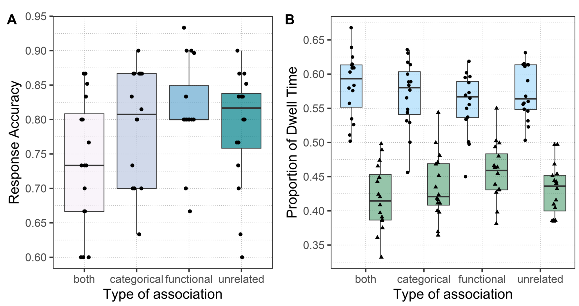

Figure 4: Box plots of the dependent measures from the recognition phase. (A) Response accuracy (expressed as a proportion) to recognise the familiar object across the four types of conceptual association. (B) The proportion of time spent on the novel (green) vs the familiar (light sky blue) object across the types of association. The hinges of the boxplots represent the 25th and 75th percentiles of the measure (lower and upper quartiles), while the horizontal line represents the median of the distribution. Each dot indicates the by-participant average for that measure.

General Discussion

The tendency of observers to orient their overt attention towards novel information in the visual context has been taken as an indirect index of memory processes. However, the available literature on this cognitive mechanism has not detailed the temporal dynamics of the novelty preference, nor has it examined whether the organisation of semantic knowledge significantly modulates the strength of its effect.

First, our study uncovered a modulation in the NP due to the time between the familiarisation and the test phase. As the delay between these two phases increased from .6 seconds to 2 minutes, participants looked significantly more at the novel object. We propose two alternative explanations for this result. One possibility is that at shorter retention intervals, attention may be mostly oriented towards the familiar object, which is still strongly active in visual short-term memory. This mechanism gradually weakens for increasing delays, which may reflect a systematic decrease of memory for the familiar object. Alternatively, this outcome may relate to short-term memory's "primacy" effect (Baddeley, 2000; Tulving, 2008). Pairs presented at the longest delays were also the first to be encoded, explaining the increase in NP over delays, i.e., an indicator of implicit memory of the familiar object.

Second, NP was directly modulated by the conceptual association between the two objects studied. NP was weaker for pairs of objects familiarised as categorically and functionally related. However, this effect was modulated over time, making it stronger for increasing delays. This conceptual association may be the strongest as it promotes a categorical and functional relationship between the two objects, possibly encoding them as a unitary memory trace. Therefore, when only a part of this integrated whole is presented during the test phase, it attracts attention to validate the previously established association. However, as the time between familiarisation and the test increases, the NP increases, indicating that the conceptual association between the two objects may progressively wane in memory.

It is worth noting that in the traditional version of the VPC, participants were presented with two identical copies of a stimulus. Typically, during the test phase, the stimulus that had been seen before tended to attract less attention as it was already familiar and stored in memory, thus becoming "less interesting". However, participants are presented with two distinct objects during encoding in the current setup. Consequently, it is not surprising that these objects attract more attention when one reappears without the other, especially when encoded as strongly conceptually associated. We suggest that the strength of conceptual association between the objects affected the expectation of seeing them together again. As this expectation is violated (i.e., during the test phase), it creates a memory mismatch, prompting participants to spend more time observing the familiar object to resolve this conflict. However, this trend progressively reduces as the temporal distance between familiarization and test increases. At the longest delay (i.e., 2 minutes), there is no appreciable difference between the four types of associations (refer to Figure 3C). The fact that the conceptual organisation of semantic knowledge directly influences novelty preference is suggestive of an interdependence between existing semantic knowledge and memory processes (Kowialiewski & Majerus, 2020; Starr et al., 2020), highlighting effects that cannot simply be attributed to low-level features of individual items.

Successful recognitions were also characterised by participants spending more time looking at the familiar object than the novel one, especially for pairs in *both* conditions compared to the *categorical* and *functional* conditions. Indeed, novelty preference negatively predicted accuracy performance during the recognition phase. This finding confirms the interplay between novelty preferences and memory mechanisms while pointing at the role played by the type of conceptual associations participants were familiar with. The allocation of attention reflects this during the recognition process.

One puzzling result in our study was that participants were less accurate in recognising the familiar object when encoded in the strongest associative condition (i.e., *both*). As hinted, we speculate that this effect may have been driven by a re-learning that occurred during the test between a familiar object and an unrelated novel object. This intrusion may have degraded the fidelity of the memory trace of the original pair with an updated association or have caused interference due to the incongruency. However, why this phenomenon manifested in the *both* condition requires further investigation. We are now working on a novel design, more aligned with the procedure by Crutcher et al., 2019, where we will assess memory for whole pairs rather than individual objects to examine whether the direction of conceptual effects emerging in this study is maintained or disconfirmed.

Another difference with previous literature is that the magnitude of the NP is much reduced in our study (i.e., ~ 55% compared to 75% in Crutcher et al., 2009). One possibility is that our familiarisation phase was shorter than this work, i.e., 2 seconds compared to 5 seconds; longer familiarisation times may lead to stronger NP (e.g., Richmond et al., 2004). Moreover, we did not familiarise our participants more than once. Repetition can boost memory capacity (Chen & Yang, 2020) and decrease the overt attention needed to acquire familiar information (Heisz & Ryan, 2011).

In sum, our study provides new evidence regarding the influence of conceptual knowledge on memory processes, as indexed by novelty preference. Novelty preference progressively increased over a short temporal window and was mediated by the organisation of conceptual knowledge. These findings are relevant for understanding cognitive changes in ageing, especially in pathological conditions, as they highlight intricate conceptual and temporal relationships in short-term visual memory processes that must be considered when designing screening tools to detect early signs of prodromal dementia.

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