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# Dissociating refreshing and elaboration by their neural signatures and their effects on memory in young and old adults

Lea M. Bartsch
University of Zurich and University Priority Program Dynamics of Healthy Aging

Vanessa M. Loaiza
University of Essex

Lutz Jäncke
University of Zurich and University Priority Program Dynamics of Healthy Aging

Klaus Oberauer
University of Zurich and University Priority Program Dynamics of Healthy Aging

Jarrod A. Lewis-Peacock
University of Texas at Austin

Author Note

Correspondence should be addressed to Lea M. Bartsch, Department of Psychology, Cognitive Psychology Unit, University of Zurich, Binzmuehlestrasse 14/22, 8050 Zurich, Switzerland. E-mail: l.bartsch@psychologie.uzh.ch. Tel: +41 44 635 74 61

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**Abstract**

Maintenance of information in working memory (WM) is assumed to rely on *refreshing* and *elaboration*, but clear mechanistic descriptions of these cognitive processes are lacking, and it is unclear whether they are simply two labels for the same process. This fMRI study investigated the extent to which refreshing, elaboration, and repeating of items in WM are distinct neural processes with dissociable behavioral outcomes in WM and long-term memory (LTM). Multivariate pattern analyses of fMRI data revealed differentiable neural signatures for these processes, and the degree of neural separation within an individual predicted their memory performance. The benefit of refreshing items in WM increased as its neural signature became more similar to repetition. Elaboration improved LTM, but not WM, and this benefit increased as its neural signature became more distinct from repetition. This demonstrates that refreshing and elaboration are separate processes that have predictable contributions to memory performance.

*Keywords*: Refreshing, Elaboration, Working memory, Long-term memory, MVPA

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## Introduction

Working memory (WM) is a system for holding a limited amount of information available for processing (Baddeley, 1986), whereas episodic long-term memory (LTM) stores information permanently with presumably unlimited capacity (Tulving, 1972). WM and LTM are highly correlated constructs, and models on their relation suggest that how information is processed in WM strongly affects how well it is maintained in LTM. (D'Esposito & Postle, 2015; Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015; Lewis-Peacock & Postle, 2008; Ranganath, 2006; Ranganath & Blumenfeld, 2005; Ranganath, Cohen, & Brozinsky, 2005; Crowder, 1982; Melton, 1963; Nairne, 1990, 2002; Cowan, 1995; Oberauer, 2002). Thereby, two control processes on information in WM have been argued to contribute to encoding in episodic LTM: *refreshing* and *elaboration*. The aim of the present study is to investigate (1) whether refreshing and elaboration are neurally and behaviorally distinguishable processes, (2) how they affect WM and episodic LTM performance, and (3) to what extent age differences in these processes are responsible for memory deficits in older adults.

### Refreshing and elaboration: Definitions and behavioral impacts on WM and LTM

Refreshing is understood as briefly thinking of a stimulus just after it is no longer physically present but while its representation is still active (Johnson, Reeder, Raye, & Mitchell, 2002). The process was introduced as a general attention-based mechanism for enhancing and prolonging the activation of memoranda in WM (see Camos et al., 2018 for a review), thereby improving WM (Souza & Oberauer, 2016; Souza, Vergauwe, & Oberauer, 2018; but see for contradicting evidence Bartsch, Singmann, & Oberauer, 2018) and episodic LTM (Johnson et al., 2002). Researchers debate how refreshing operates, with views depending on their understanding

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of the WM-LTM relationship and what constitutes a WM representation. Some argue that refreshing strengthens content-context bindings and thereby creates stronger retrieval-cues for WM and LTM (Lewandowsky & Farrell, 2008; Loaiza & McCabe, 2012; Oberauer & Hein, 2012; Oberauer & Lewandowsky, 2011). Others understand refreshing as a mechanism for preserving representations against decay (Barrouillet & Camos, 2015; Lemaire, Pageot, Plancher, & Portrat, 2017).

Still another possibility is that the purported benefits of refreshing simply reflect elaboration. Elaboration refers the act of deeply processing information, especially with regard to its semantic and meaningful characteristics (Craik & Lockhart, 1972; Greene, 1987; Klatsky, 1988), and, as consequence, reliably improves episodic LTM (e.g., Craik & Tulving, 1975; Gallo, Meadow, Johnson, & Foster, 2008). The benefits of elaboration for WM are more mixed: Correlational studies show a positive relationship between elaborative strategies and verbal WM recall (Bailey, Dunlosky, & Kane, 2008, 2011; Dunlosky & Kane, 2007; Kaakinen & Hyönä, 2007) and some experimental work has shown that semantic compared to shallow processing of the memoranda yields greater WM recall (Loaiza, McCabe, Youngblood, Rose, & Myerson, 2011; Rose, Buchsbaum, & Craik, 2014; Rose, Craik, & Buchsbaum, 2014). Conversely, other work has shown unique benefits of elaboration for episodic LTM and not WM (Bartsch, Singmann, & Oberauer, 2018; Loaiza & Camos, 2016; Rose & Craik, 2012; Rose et al., 2010). Bartsch and colleagues showed that elaboration benefited LTM, but refreshing did not, and neither elaboration nor refreshing benefited WM. Furthermore, Loaiza and Camos (2018) showed that the benefit of semantic retrieval cues for verbal WM was independent of factors intended to manipulate refreshing. These studies collectively demonstrate that any refreshing benefit in WM does not result from interacting with LTM representations, thereby differentiating

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refreshing from elaboration. Despite these findings, it may be the case that refreshing and elaboration produce different outcomes that are derived from the same underlying process. To address this, we turn to neuroimaging data.

**Refreshing vs. elaboration: Neural correlates**

Table 1 shows an overview of all the reported regions associated with refreshing and/or elaboration. Refreshing has been associated with activity in the left dorsolateral prefrontal cortex (dlPFC, BA 8/9) and better LTM recognition compared to repeating the stimuli, and activity in the dlPFC during refreshing predicted subsequent LTM (Johnson, Raye, Mitchell, Greene, & Adam, 2003; Raye, Johnson, Mitchell, Greene, & Johnson, 2007; Raye, Johnson, Mitchell, Reeder, & Greene, 2002) A meta-analysis (Johnson et al., 2005) identified frontal regions, specifically left dlPFC (BA 9/46), ventrolateral PFC (vlPFC, BA 44/45/47), and the left anterior PFC (BA 10) as associates of refreshing various stimulus material.

Although the dlPFC has been suggested to underlie refreshing, its activation has also been shown to predict subsequent LTM in studies of elaboration (or "relational encoding") wherein the semantic relationship between two items is elaborated upon (e.g. Blumenfeld & Ranganath, 2007). For the ease of the reader, we will refer to *relational encoding* as *elaboration* from now on. The neural correlates of elaboration have not always been that specific or limited to the dlPFC: earlier studies have more generally associated the lateral PFC with semantic elaboration (e.g., Kapur et al., 1994; Wagner et al., 1998) and relational elaboration (e.g., Addis & McAndrews, 2006; Fletcher, Shallice, & Dolan, 2000; Murray & Ranganath, 2007). Yet, numerous studies have associated the dlPFC with elaboration and subsequent memory effects (Blumenfeld, Parks, & Yonelinas, 2010; Blumenfeld & Ranganath, 2007; Davachi, Maril, &

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Wagner, 2001; Ragland et al., 2012). Collectively, this evidence suggests that elaboration of the memoranda in WM is what makes the dlPFC important for LTM.

Despite the neural similarities observed for refreshing and elaboration, there are some important dissimilarities in the methods used to study these processes. First, the neural correlates of refreshing have been studied for single items only, with no instructed elaboration (e.g. Johnson et al., 2005; Raye et al., 2007, 2002), and this item-specific neural processing was localized almost exclusively to left lateral dlPFC. Conversely, elaboration studies have used multiple items, such as pairs (Blumenfeld et al., 2010) or triplets of words (e.g. Blumenfeld, 2006; Davachi, Maril, & Wagner, 2001), and localized the associated activity to the bilateral dlPFC. Second, the refreshing studies have relied on incidental encoding, wherein participants are not informed of the upcoming memory test, whereas the elaboration studies employ intentional encoding. Thus, clarifying the underlying neural processes of refreshing and elaboration requires greater consistency between the methods used to investigate them.

**Refreshing and elaboration: Age effects**

Past research has provided extensive evidence that episodic LTM declines with age (e.g., Hoyer & Verhaeghen, 2006; Naveh-Benjamin & Old, 2008; Zacks, Hasher, & Li, 2000), but the source of the deficit is still under debate. One view is that WM maintenance processes and recruitment of corresponding brain areas decline in older age (Hoareau, Lemaire, Portrat, & Plancher, 2016; Plancher, Boyer, Lemaire, & Portrat, 2017; Smith, 1980). For instance, it has been shown that older adults exhibit reduced refreshing-related brain activity in the left dlPFC and reduced refreshing benefits for episodic LTM relative to young adults (Johnson, Mitchell, Raye, & Greene, 2004; Raye, Mitchell, Reeder, Greene, & Johnson, 2008). Another possibility is that

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older adults are less likely than younger adults to engage in elaboration, thereby resulting in deficient retention (Smith, 1980). For example, some work has shown older adults are able to capitalize on experiment-administered elaborative strategies but show deficiencies in generating elaborative strategies themselves (Rankin & Collins, 1985, see also Kamp & Zimmer, 2015). A meta-analysis reported that age-related differences in subsequent memory are associated with under-recruitment of the occipital and fusiform cortex as well as an over-recruitment of medial and lateral regions of PFC and parietal lobe (Maillet & Rajah, 2014). These findings suggest inefficient recruitment of brain regions that are important for elaboration, thereby leading to age-related memory deficits.

**The present study**

The goal of the present study was to investigate to what extent elaboration and refreshing are separable processes, given their neural overlap as well as their similar proposed beneficial effects for memory. So far, only one study has investigated both processes in one experiment, and the behavioral results demonstrated that the processes have divergent contributions to LTM (Bartsch et al., 2018). We aimed at extending this previous study by not only investigating whether refreshing and elaboration are distinct in their contribution to WM and LTM formation, but also whether they are supported by separable neural activation patterns. Furthermore, we aimed to investigate their impact on age-related memory deficits.

We applied multivariate pattern analyses (MVPA; e.g., Haxby, Connolly, & Guntupalli, 2014; Haxby et al., 2001; Haynes & Rees, 2006; Lewis-Peacock & Norman, 2014; Norman, Polyn, Detre, & Haxby, 2006) to fMRI data of young adults and older adults performing the word list encoding task of Bartsch et al. (2018). This analysis approach allowed us to evaluate

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whether brain activity patterns associated with refreshing items and with elaborating items in WM could be differentiated. These neural measures were then linked to behavioral outcomes on tests of both WM and LTM. MVPA is especially sensitive to detecting fine-grain differences between neural activation patterns that are not detectable using conventional analyses (N Kriegeskorte & Bandettini, 2007).

If refreshing and elaboration are two labels for the same process, then the pattern of behavioral effects should be similar for WM and on LTM, and the patterns of brain activity supporting these processes should be indistinguishable. If refreshing and elaboration are distinct processes, they should have different behavioral effects and separable patterns of neural activation. As elaboration has previously been shown to benefit LTM compared to re-reading the memory material, we expected the greatest LTM benefit when the neural signatures of elaboration and repetition were most distinct. On the other hand, because re-reading has been shown to benefit WM *more* than refreshing, we expected the greatest benefit of refreshing when these processes were most similar. Finally, if older adults' memory deficits are caused by deficient uses of refreshing and elaboration, we expected their neural signatures to be less distinct and more weakly correlated with behavioral outcomes compared to young adults.

## Method

### Subjects and general procedure

We recruited 30 healthy, right-handed young adults (15 females; mean age = 24.2, SD = 2.97 years) from the student population of the University of Zurich as well as 27 healthy, right-handed older adults from the community (13 females; mean age = 69, SD = 3.47 years). Handedness was measured through observation of the writing hand. Subjects were screened for

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their ability to undergo a magnetic resonance imaging session. Furthermore, they completed the Digit–Symbol Substitution test (DSS; Wechsler, 1982), serving as an indicator of processing speed, and the mini-mental-status examination (MMSE; Folstein, Folstein, & McHugh, 1975) to screen for cognitive impairment. All subjects performed a WM task while being scanned with a 3-T MRI scanner, and subsequently an LTM task outside the scanner. The session ended with a computerized version of a vocabulary test (Lehrl, 2005), a marker test for crystalized intelligence. The study was approved by the ethical review board of the canton of Zurich. The participants were compensated with either 60 Swiss Francs (about 60 USD) or partial course credit for the two-hour session.

**Paradigm**

The paradigm is the same as reported in a recent study (Bartsch et al., 2018), adapted for use in the MRI scanner. We asked participants to remember six nouns in serial order (see

Figure 1). After list presentation, either the first three words or the last three words were to be processed again in one of four ways, depending on the experimental condition. During encoding it was not predictable which half of the items would have to be processed. In the *repeat* condition, the three words appeared again sequentially on the screen, and the subjects had to simply re-read them silently (we will also refer to this as the *re-read* condition). In the *refreshing* condition, the to-be-processed words were replaced by refreshing prompts appearing at the same location. The subjects were instructed to "think of" the corresponding words as soon as the prompts were shown. In the *elaboration* condition, the three to-be-processed words were shown again sequentially on the screen, and subjects were instructed to generate a vivid mental image of the three objects interacting. The stimuli appearing on the screen in that condition did not differ

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from the repeat condition, leaving the instruction to form a vivid mental image as the only difference between these conditions. Finally, in the combined *refresh-with-elaboration* condition the participants had to "think of" the words replaced by the prompts, and additionally form a vivid mental image of those items. Again, the event sequence of this condition does not differ from the refreshing condition apart from the instruction to form a mental image. Memory was tested with a four-alternatives forced-choice task, which we describe in detail below (see Section Procedure: Working memory task).

The experiment used a 2 x 2 x 2 x 2 (repeat/refresh [repeat, refresh] x elaboration [with elaboration, without elaboration] x processing [processed triplet, unprocessed triplet] x age [young adults, older adults]) within-subject, between-age group design. Orienting the processing task to only a subset of the words in memory allows us to draw inferences about the effect of each of the processing conditions on memory by comparing the memory performance of the triplet of words that was not further processed after encoding to the triplet that was processed according to one of the four experimental conditions.

**Materials**

The stimuli were nouns randomly drawn from a pool of 863 German abstract and concrete nouns for each subject. The nouns were between two and 15 letters long and had a mean normalized lemma frequency of 30.81/million (drawn from the dlexdb.de lexical database).

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**Procedure: Working memory task**

The sequence of an experimental trial is illustrated in

Figure 1. The experiment was performed using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). The six to-be-remembered words in each trial were sequentially presented in boxes from top to bottom on the screen, each for 500 ms. Depending on the experimental condition, a cue was presented 1000 ms after the last memory item, indicating whether the first half or the second half of the list had to be processed again. In the elaboration and repeat conditions, each word in the to-be-processed triplet was shown again for 1400 ms, followed by a 600 ms inter-stimulus interval. In the refreshing and refreshing-with-elaboration conditions, each to-be-processed word of a triplet was replaced by a refreshing prompt (#?#?#) in its corresponding box, and participants were instructed to "think of" the word in that box. In the elaboration and refresh-with-elaboration conditions, participants were additionally instructed to form a vivid mental image of the three words interacting with each other.[1]

After processing the words in the cued triplet, participants' memory for each list item was tested in their order of presentation using a 4-alternative forced-choice procedure. For each tested item, four words were presented from which the subject could choose the correct word in the currently tested list position with a button press. All test sets included the following four response options: the target (i.e., correct) word, one lure from the same triplet of words within

[1] The timing parameters where chosen based on a pilot experiment with young adults, which allowed participants to process the items in each of the 4 experimental conditions in a self-paced mode. The mean processing times (PT) where PT = 1419 ms in the repeat without elaboration condition, PT = 1491 ms in the repeat with elaboration condition, PT = 1197 ms in the refreshing without elaboration, and PT = 1198 ms in the refreshing with elaboration condition.

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the present list, one lure from the other triplet of the present list, and one new word. This choice had to be made for each of the serial positions successively and with a time limit of 2500 ms for the young and 3500 ms for the older adults per serial position to ensure controlled timing for the fMRI image acquisition. We applied this 4-alternatives forced-choice recognition task in order to test both memory for items (i.e., discriminating between items that have been presented in the current memory list and new items) and for serial order (i.e., discriminating between the item in the tested position and other list items).

Within each block of four trials, the same type of processing was instructed throughout, and a screen repeating the instructions of the particular condition was shown prior to the beginning of each block. The order of the condition blocks was randomized between subjects. Each of the four fMRI runs consisted of four blocks, one for each condition (with 4 trials per block as described above).

**Procedure: Long-term memory task**

After leaving the scanner participants were brought into a separate room, where they performed the computerized LTM task. We assessed participants' LTM for the words they had encoded for the WM tests throughout the experiment. To this end, we presented in each trial the first word of a triplet from one of the studied memory lists. We asked participants to choose, from four different options, the word that had followed the target word in that triplet. The probe words included the correct word (i.e., which could be either the word in the second or third position of the target triplet for the first prompt, and the fifth or sixth word for the second prompt), two words from another list, and a new word. This allowed us to keep the format of the LTM test very similar to the WM test, and furthermore to compare in each trial the memory performance for words from the processed and from the unprocessed triplets. As in the WM test,

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the LTM test also provided information about both item memory (i.e., which words have been presented in the experiment) and relational memory (i.e., which words have been together in a triplet). The participants were made aware of the LTM test before the start of the experiment.

**fMRI Data Acquisition and Preprocessing**

Whole brain images were acquired with the 3 T Philips Ingenia MRI scanner with a 32-channel head coil, located at the University Hospital Zurich, Switzerland. High-resolution T1-weighted images were acquired for all subjects with a Turbo field echo (TFE) sequence (8ms time repetition (TR), 3.7ms time echo (TE), 8° flip angle, 160 sagittal slices, 240 × 240 inplane, 1.0mm isotropic). Blood oxygen level-dependent (BOLD)-sensitive functional MRI data were acquired using a gradient-echo, echo planar sequence (2 s TR, 35ms TE) within a 72 × 70 matrix (32 transverse slices, 3 mm isotropic).

Following the acquisition of the structural images, four MRI acquisition runs were collected for each subject, in which they performed a 10-min block of a six-item WM task with a processing delay. fMRI data preprocessing (slice-time correction and realignment) was performed with SPM12 (Penny, Friston, Ashburner, Kiebel, & Nichols, 2011). Subjects' functional scans were aligned by realigning the first volume in each run to the first volume of the first run, and then registering each image in each run to the first volume of that run. The middle functional slice served as a reference for slice-time correction. Further, the functional volumes were co-registered to the T1 anatomical image.

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**Analysis of Behavioral Data**

All data and analysis scripts can be assessed on the Open Science Framework (osf.io/p2h8b/).We analyzed the behavioral data using a Bayesian generalized linear mixed model (BGLMM) implemented in the R package *rstanarm* (Stan Development Team, 2018) following the exact analysis pipeline reported by Bartsch and colleagues (2018). The dependent variable was the number of correct and incorrect responses in each cell of the design per participant. Correct responses were defined as choosing the target item from the four alternatives. Bayesian procedures provide posterior probability distributions of the model parameters (i.e., the regression weights) that express uncertainty about the estimated parameters. The highest density regions (HDRs) of these posteriors can be used for statistical inference. A 95% HDR represents the range in which the true value of a parameter lies with probability 0.95, given model and data (Morey, Hoekstra, Rouder, Lee, & Wagenmakers, 2016). If zero lies outside the Bayesian HDR there is strong evidence for the existence of the corresponding effect. Although the strength of evidence varies continuously, for simplicity we will describe effects as "credible" if their HDRs exclude zero. We used an MCMC algorithm (implemented in Stan; Carpenter et al., 2017) that estimated the posteriors by sampling parameter values proportional to the product of prior and likelihood. These samples are generated through 4 independent Markov chains, with 1000 warmup samples each, followed by 1000 samples drawn from the posterior distribution which were retained for analysis. Following Gelman and colleagues (2013), we confirmed that the 4 chains converged to the same posterior distribution by verifying that the $\hat{R}$ statistic – reflecting the ratio of between-chain variance to within-chain variance – was $< 1.01$ for all parameters, and we visually inspected the chains for convergence.

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**Generation of ROIs**

We included all ROIs that were previously reported in fMRI studies investigating either refreshing or elaboration and that had shown subsequent memory effects and/or significant activation differences between repeating and refreshing or elaboration in univariate analyses (see Table 1 for details). This search was performed using the neurosynth.org database and keyword-based search in pubmed.gov. Anatomical ROIs were generated using an automated parcellation method from *FreeSurfer*. Briefly, a surface mesh model was reconstructed for each subject. Each subject's surface was then auto-parcellated based on the folding pattern of the gyri and sulci. We generated ROIs corresponding to frontal, parietal, fusiform, parahippocampal and temporal regions in this manner. We constructed combined masks using *fslmaths* to create the frontal mask, encompassing Brodmann areas 44, 45, and 47 for the inferior frontal mask, and including Brodmann areas 4, 6, 8, 9, 10 and 46 for the superior frontal mask. The parietal mask included Brodmann area 3, 7 and 40. The temporal mask consisted of the inferior-, middle-, and superior temporal labels of the *aparc* atlas and the fusiform mask consisted of the fusiform label of the atlas. We further combined masks with *fslmaths* in various combinations of the above (e.g. frontal-parietal mask, frontal-temporal-parietal mask, frontal-fusiform mask, frontal-fusiform--parietal mask).

**Multivariate Pattern Analyses of fMRI Data**

MVPA provides greater inferential power than classical univariate approaches due to its higher sensitivity at detecting information in neural signals. As a result, MVPA has led to the successful within-category decoding of the contents of WM at an item level (LaRocque, Riggall,

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Emrich, & Postle, 2017) as well as the characterization of neural representations in different states of WM (Christophel, Iamshchinina, Yan, Allefeld, & Haynes, 2018; Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012; Lewis-Peacock, Drysdale, & Postle, 2015; Rose et al., 2016). The sensitivity of MVPA was further established by a study demonstrating that allegedly category-selective brain regions detected in univariate analyses of the BOLD signal during the delay period of a WM task still carried patterns of activity associated with another category of information, that was currently relevant for behavior (Lewis-Peacock & Postle, 2012).

MVPA was performed in MATLAB using the Princeton MVPA toolbox (http://code.google.com/p/princeton-mvpa-toolbox). The classification algorithm used for this analysis was a L2-regularized binary logistic regression (1 vs. the others), that uses Carl Rasmussen's conjugate gradient minimization algorithm, with a penalty term of 50. The classification was performed in the anatomically defined ROIs defined above. All neural data were high-pass filtered with a cut-off of 128 seconds and z-scored across trials, within runs, before running MVPA. We performed ANOVA-based feature selection of all active voxels within the respective ROI mask and chose the voxels that individually were able to discriminate between the three conditions (repeat, refreshing, elaboration) significantly ($p < .05$) over the course of the experiment. To avoid circularity in the data analysis, feature selection was performed separately for each iteration of the cross-validation classifier training algorithm, using only the training and testing sets independentdata in each iteration (Kriegeskorte, Simmons, Bellgowan, & Baker, 2009). This univariate feature selection technique has been shown to reliably improve classification accuracy in MVPA of fMRI (Lewis-Peacock & Norman, 2014). The pattern of activity across these feature-selected voxels was used as the input to the pattern classifier.

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***MVPA — Three-way problem: repeat vs. refreshing vs. elaboration.***

The classification procedure used k-fold cross-validation on the data from the WM task. Preprocessed fMRI data from each 6-s processing period (three volumes) from the WM trials, after accounting for a 6-s hemodynamic lag, were used for the analysis. Our analysis scheme incorporated each functional volume (acquired over a 2-s TR) as a separate training event, so that every trial resulted in three events. Each event was associated with an array of features corresponding to BOLD signal in voxels in the ROI being used.

The k-fold cross-validation scheme (k = 4, for each of the runs) trained a classifier, separately for each participant, on the data of the three conditions (repeat, refresh and elaboration) from three runs and then used this classifier to test the data from the withheld run. This process was repeated until every run had been held out for testing. The statistical significance of classifier accuracy was evaluated by performing permutation tests on relabeled training data, in each cross-validation fold, and comparing the resulting distribution of classifier accuracies to the true (unshuffled labels) classifier accuracy with a one-sample, one-tailed t-test. This analysis scheme was performed for every ROI. Finally, classification performance was also assessed using receiver operating characteristic (ROC) curves, which rank the classification outputs according to their probability estimates (from strongly favoring Class A to strongly favoring Class B or C) and chart the relationship between the classifier's *true positive rate* (probability of correctly labeling examples of Class A as Class A) and *false positive rate* (probability of incorrectly labeling examples of Class B or C as Class A) across a range of decision boundaries. The area under the curve (AUC) indexes the mean accuracy with which a

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randomly chosen pair of Class A and Class B (or C) trials could be assigned to their correct classes (0.5 = random performance; 1.0 = perfect performance).

***MVPA — Two-way problems: repeat vs. refreshing and repeat vs. elaboration.***

In order to assess how the neural classification of the refreshing process as well as the neural classification of the elaboration process relates to an individual's task performance, we used the repeat condition as a reference. First, we extracted classification scores from repeat and refresh trials only, using classifiers that were trained on all three processes. In order to assess the neural separability of the perceptually identical conditions of repeat and elaboration, we chose to retrieve the evidence values of the two-way problem from the three-way trained classifier the same way as we did for the repeat vs. refreshing comparison, with the difference that we did this for each individuals' mask with the *highest* classifier accuracy. The reason for this is that elaboration instruction (*"form a vivid mental image of the three words interacting with each other"*) can be implemented very differently by each subject, resulting in unique subject-specific neural signatures of elaboration. Here, our primary interest was to discover *whether* elaboration could be identified and distinguished, rather than to identify precisely *where* in the brain the processes were implemented. Once again, we assessed classifier performance for each binary classification problem using AUC.

***MVPA — refreshing with elaboration.***

We were further interested in whether the patterns of activity in the brain during the combined refreshing with elaboration condition would be similar to refreshing or to elaboration or would elicit neural patterns of a completely new process.

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Equivalent to the above analysis scheme we trained classifiers on all four conditions (repeat, refreshing, elaboration, and simultaneous refreshing and elaboration) and then we extracted classification scores from refreshing with elaboration trials only, using classifiers that were trained on all four processes, again in a k-fold cross-validation scheme. In order to assess the neural separability of the conditions of refreshing, elaboration, and refreshing with elaboration, we chose to retrieve the evidence values of *refresh*, *elaborate* and *refresh with elaboration* from the four-way trained classified. With this approach of training on a four-way-problem and testing on three processes, we computed the evidence values for refreshing, elaboration or the refreshing with elaboration condition. This allowed us to explore whether the brain activation patterns of the combined refreshing with elaboration events were more similar to refreshing or to elaborating or elicited a completely different process (note that classifier evidence can be construed as an estimate of the similarity between patterns of activity, with high evidence values implying low similarity of the target condition to all other conditions, and vice versa). Using k-fold cross-validation, we trained classifiers on three runs of data and tested it on the withheld run, but only on trials from the refreshing with elaboration condition. Note that it was important to include the repeat condition in the training set to help the classifier distinguish unique process-level activity associated with the perceptually identical elaboration condition.

**Researcher Degrees of Freedom**

Analyses of neural data involve many decisions, and when these decisions are informed by the data to be analyzed, there is a risk that they are biased in favor of a desired outcome (Simmons, Nelson, & Simonsohn, 2011). Some aspects of our analysis plan (in particular, the decision to use anatomically defined ROIs for the MVPA analyses) were informed by the data of the young adults. Our analysis of the old adults' data, however, used the exact same analysis

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pipeline as that for the young adults without any adjustment informed by the old adults' data. Therefore, any convergent finding in both age groups can be thought of as having been directly replicated in a different population. For any finding that differs between age groups, there remains an ambiguity as to whether the divergence reflects a failure to replicate the finding in the young-adult sample, or a genuine age difference. Resolving this ambiguity requires a replication of the entire study with the present analysis plan.

## Results

### Behavioral Results

We replicated all effects of the young adults reported in a previous study (Bartsch et al. 2018). Figure 2 shows the estimated proportion of correct responses and their corresponding 95% highest posterior density regions for the immediate and delayed memory data. The posterior effect estimates are presented in Table 2 and Table 3. A first question was whether our manipulation of processing half of a memory list had an effect on memory. The credible main effect of processing on immediate and delayed memory supported an effect of our manipulation: Participants had better memory for items that were processed again after initial encoding than for items from the unprocessed triplets (see Table 2 & Table 3 and Figure 2). There was also a main effect of age, such that older adults showed worse memory performance on tests of both WM and LTM.

***Working memory performance.*** We first tested how the effect of refreshing a subset of words in WM compares to the effect of repeated reading of these words. This is the comparison through which Johnson and colleagues evaluated the effect of refreshing on delayed memory (Johnson et al., 2002; Raye et al., 2007). There was a main effect of repeat/refresh (Table 2), but

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with an advantage of repeating over refreshing. This main effect was further qualified by the two-way interaction of processing and repeat/refresh, indicating that repeated words benefited more from being processed again than refreshed words did. Nevertheless, the effect of processing appeared for both repeated words ($\Delta = 0.34$, 95% HDR = [0.31, 0.37]) and refreshed words ($\Delta = 0.12$, 95% HDR = [0.10, 0.15]). Furthermore, the factor of repeat/refresh interacted with age, indicating that older adults had a greater advantage of repeat over refreshed trials than young adults. Nevertheless, the repeat-refresh difference appeared for both, young ($\Delta = 0.16$, 95% HDR = [0.13, 0.18]) and older adults ($\Delta = 0.09$, 95% HDR = [0.06, 0.12]).

The BGLMM revealed no credible evidence for a main effect of elaboration on WM performance, or for any of the interactions involving elaboration (see Table 2).

***Long-term memory performance.*** The BGLMM revealed evidence for a main effect of repeat/refresh on LTM performance, but as with WM, there was an advantage for repeating over refreshing (see Table *3*). There was no evidence for any further interaction including the repeat/refresh factor. Hence, contrary to the findings of Johnson and colleagues, refreshing did not lead to better LTM than repeated reading. Note that the above pattern of results also holds for a lenient score of performance in the LTM task, counting all responses showing correct item memory (i.e. the target, same-list items, and other-list items) as correct responses.

Furthermore*,* the analysis of the LTM data revealed evidence for an interaction of elaboration with age (see Table *3*). Follow-up analyses of the interaction revealed that a beneficial effect of elaboration appeared only for young ($\Delta = 0.05$, 95% HDR = [0.02, 0.06]), but not older adults ($\Delta = -0.01$, 95% HDR = [-0.04, 0.3]). In sum, memory was better for trials with instructed elaboration than for those without, but only for the young and not the older adults. The

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above evidence speaks for an age-dependent beneficial effect of elaboration on LTM that is lost in older age.

To summarize, our results provide no evidence for an effect of refreshing on LTM for either age group; instead we replicated the benefit of elaboration on LTM but only for young adults.

## MVPA Results

### Young adults

#### *Repeat vs. Refresh vs. Elaborate.*

The classification scores for each individual were converted to a sensitivity score, accounting for both hits and false alarms, by computing the area under the ROC curve (AUC) for the three-way classification. For 25 of the 30 subjects classification of repeat, refresh, and elaborate processes was successful ($M_{AUC}$ = 57.17 %, $SD_{AUC}$ = 4.16%, i.e., significantly better than chance with $p < .05$) in at least one of the predefined anatomical ROIs (see Methods) (Figure 3b). Mean classification sensitivity for these 25 subjects in their significant ROIs was $M_{AUC}$ = 57.17 % ($SD_{AUC}$ = 4.16%). Data from the five remaining subjects were excluded from the subsequent analyses. A majority of the subjects (N = 17) showed good classification in the combined bilateral frontal–fusiform–parietal regions, and the remaining subjects (N = 12) showed good classification in various subsets of this larger mask (see Figure 3). Notably, whole-brain classification was less successful than this ROI-based approached ($M_{AUC}$ = 53.49%).

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### *Linking neural classification to memory performance*

*Refresh vs. Repeat*

As in the three-way classification analysis, the classification scores for each individual were converted to a sensitivity score, accounting for both hits and false alarms, by computing the area under the ROC curve (AUC) for the *refresh* vs. *repeat* classification. The classifier AUC for separating re-reading from refreshing was well above chance in the combined mask of frontal–fusiform–parietal regions and its various subsets ($M_{AUC}$= 61.14%, $SD$ = 2.9%, chance = 50*%, p < .001-.05*; Figure 4b). These neural separability scores were then correlated with three individual behavioral metrics: (1) the *repeat processing benefit* contrasts memory for the processed triplets (i.e., the words that were re-read) vs. the unprocessed triplets in that condition, (2) the *refresh processing benefit* contrasts memory for the processed triplet (i.e., the words that were refreshed) vs. the unprocessed triplets in that condition, and (3) the *repeat-minus-refresh benefit* contrasts the memory of the processed triplets in both conditions. The *repeat processing benefit* was not significantly correlated with neural separability ($r$ = 0.146, $p$ = .485). A higher *refresh processing benefit* was significantly correlated with *lower* neural separability between *refresh* and *repeat* ($r$ = -0.591, $p$ = .0263; Figure 6

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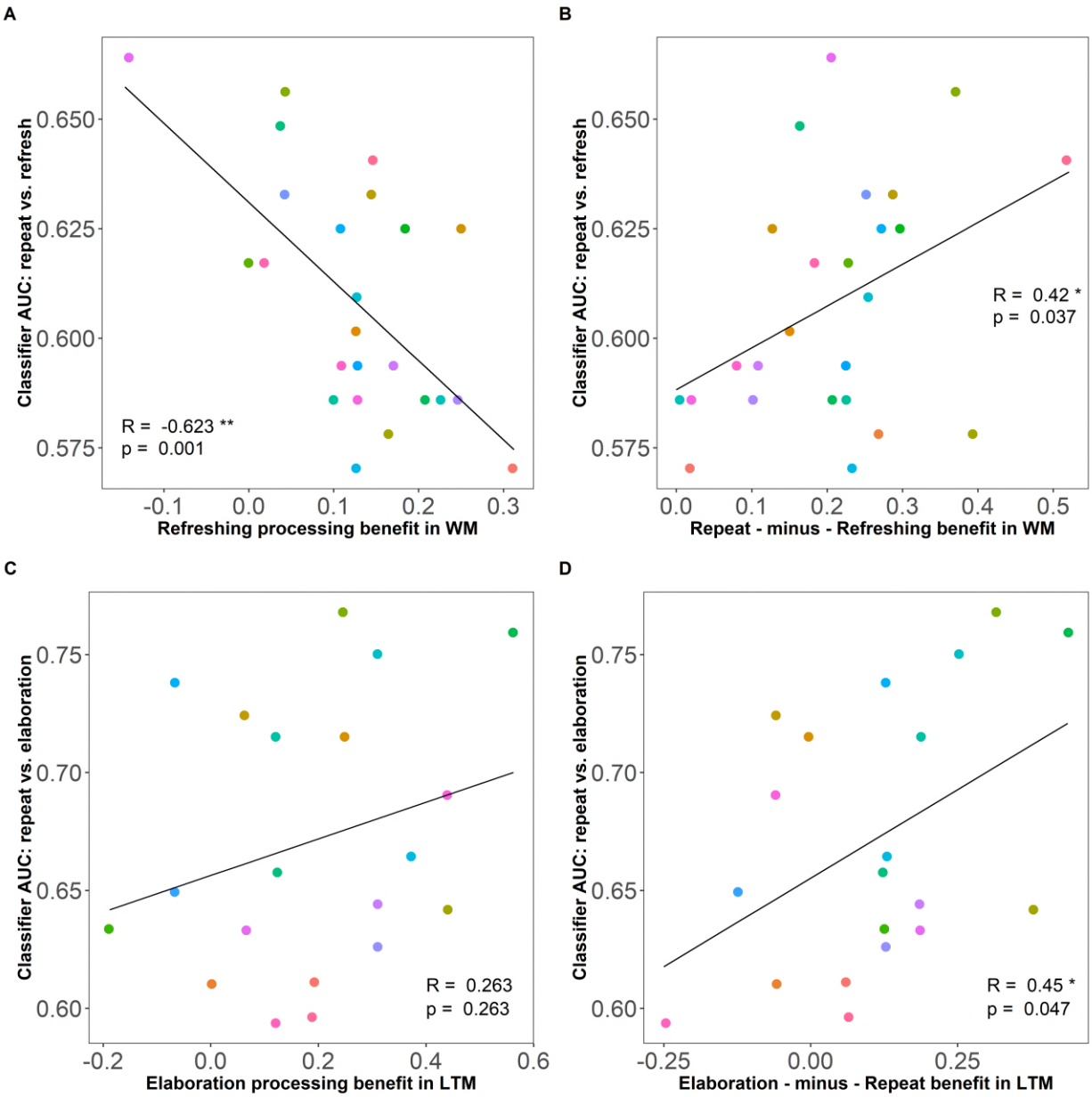


a). The more an individual benefited from refreshing parts of a list, the more neurally similar this process was to re-reading parts of a list. There was a significant positive correlation between classifier AUC scores for the *repeat vs. refresh* processes and the behavioral *repeat-minus-refresh benefit* ($r = 0.419$, $p = .047$; Figure 6b). That is, the more neurally separable *repeat* was from *refresh*, the larger the relative advantage of repeating over refreshing the words. Conversely, memory for refreshed words approximated the (higher) accuracy of repeated words when these

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neural processes were more similar. In summary, these results indicate that although repeating items benefited WM performance more than refreshing did, this relative advantage was reduced in individuals for which the neural processes of repeating and refreshing were more similar. That is, refreshing benefited WM more when it appeared, in the brain, to be more like the subject was re-reading the words.

*Elaborate vs. Repeat*

To assess how the neural classification of the elaboration process relates to an individual's task performance, we again used the repeat condition as a reference (see Methods). For 20 of the 25 subjects who showed significant classification in the three-way analysis, the processes of re-repeating and elaboration were classifiable significantly above chance in at least one mask, with a mean *AUC* of 67.11 % (*SD* = 5.67%). The individuals' best masks formed two clusters: one of bigger masks, including frontal and temporal regions (6 subjects) and the other of just frontal regions (11 subjects). The remaining 4 subjects showed highest classifiability of *repeat vs. elaborate* in temporal regions (see Figure 5b).

Elaboration had no behavioral effect on WM, but instead showed a benefit for LTM. Therefore, our analysis focused on three behavioral contrasts in the LTM accuracy data: (1) the *repeat processing benefit* contrasts memory for the processed triplets (i.e., the words that were re-read) vs. the unprocessed triplets in that condition, (2) the *elaboration processing benefit* contrasts memory for the processed triplet (i.e., the words that were elaborated) vs. the unprocessed triplets in that condition, and (3) the *elaborate-minus-repeat benefit* contrasts the memory of the processed triplets in both conditions.

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Across subjects, the relative LTM performance benefit of *elaborate–minus-repeat* was positively correlated with the classifier AUC scores reflecting the neural separation of these two processes ($r = 0.45$, $p < .05$; Figure 6d). The more these processes were separable in the brain, the more that elaboration provided a benefit for LTM beyond simply re-reading the words. Neither the *repeat processing benefit* nor the *elaboration processing benefit* were significantly correlated with neural separability ($r = 0.17$, $p = 0.487$ and $r = 0.26$, $p = 0.263$, respectively). Although the neural separability of *elaborate vs. repeat* related to the LTM performance benefit of *elaborate-minus-repeat*, we did not find such an effect on WM ($r = 0.17$, $p = 0.484$). Similar to LTM, neither the *repeat processing benefit* nor the *elaboration processing benefit* were significantly correlated with neural separability ($r = -0.12$, $p = 0.61$ and $r = -.07$, $p = 0.76$, respectively).

***Refreshing with Elaboration***

The four-way classification (repeat, refreshing, elaboration, refreshing with elaboration) yielded above chance classification in 27 out of 30 subjects, with a mean accuracy of 32.68% (*SD* = 2.95), in the combined mask of frontal–fusiform–parietal regions or its subset mask (frontal N = 3, fusiform left hemisphere N = 2, inferior frontal N = 1, inferior frontal right hemisphere N = 2, superior frontal left hemisphere N = 1). In order to assess the neural similarity of refreshing with elaboration to the individual processes of refreshing and elaboration, we used cross-validation to train a classifier and extract classifier evidence values for the *refreshing*, *elaboration,* and the *refreshing with elaboration* conditions. The classifier was applied to the held-out testing run of each fold of the cross-validation, and classifier results were extracted for each trial of the *refreshing with elaboration* condition. The evidence values across all of these trials were highly similar for each of the three trained categories. To probe further, we calculated

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the proportion of trials in this *refreshing with elaboration* condition that were classified as refreshing, elaboration, or the combined condition. Over all subjects, each of the three processes was predicted equally often. In other words, the classifier was unable to reliably distinguish the combined *refreshing with elaboration* condition from either the *refreshing* condition or the *elaboration* condition.

**Older Adults**

***Repeat vs. Refresh vs. Elaborate.***

The same analysis pipeline for the three-way problem in the young adults was subsequently applied to the independent sample of 27 older adults. For 22 subjects the classification of *repeat vs. refresh vs. elaborate* was significantly above chance in the frontal-parietal-fusiform mask or its subset masks, with a mean classifier *AUC* of 54.02 % (*SD* = 3.79%, see Figure 7b). This result indicates that the three processes were neurally separable also in older adults. Data from the five subjects for which the cross-validation classification accuracy was not significantly above chance were excluded from the subsequent analyses.

***Linking neural classification to memory performance***

*Repeat vs. Refreshing*

In order to assess how the neural classification of the processes of refreshing repeating relates to memory performance for the older adults, we again applied the same analysis approach as performed on the young adults. We retrieved the classifier *AUC* scores for separating repeating from refreshing in the 22 subjects ($M_{AUC}$ = 61.58%, *SD* = 3.36%, $p < .001$ - .05) in the combined mask of frontal–fusiform–parietal regions or in one of its subsets (Figure 8b). The AUC scores was significantly correlated to subjects' behavioral *repeat-minus-refresh benefit*: The bigger the

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repeating and refreshing was (with higher performance in the repeating condition), the more separable were the two processes in the brain, represented by higher *AUC*s ($r$ = 0.43, $p$ = .031; see Figure 10a). This is the same relation as we had observed in the young sample. In contrast to the young adults, we did not find a significant correlation of neural separability to the *refresh processing benefit* ($r$ = -0.001, $p$ = .998). Instead these neural measures were correlated with subjects' *repeat processing benefits*: Individuals with higher neural separability of re-repeating vs. refreshing showed a larger benefit for the portions of the word lists that were *repeated* ($r$ = 0.48, $p$ = .016, see Figure 10b).

In summary, the older adults' *repeat processing benefit* in WM performance was predictive of the neural separability of the two processes of repeating and refreshing. Diverging from young adults, the older adults' *refreshing processing benefit* was unrelated to the neural classifiability of these processes. This result might indicate a different, and less effective, strategy of refreshing was used by older adults compared with that of the young adults.

*Repeat vs. Elaborate*

In order to assess the neural separability of the perceptually identical conditions of repeating and elaboration in older adults, we retrieved the classifier evidence values of the *repeat* and the *elaboration* conditions from the three-way trained classifier, in this case using each individuals' mask with the highest classifier *AUC*. For 20 out of the 22 subjects that showed significant classification in the three-way analysis, the processes of repeating and elaboration were reliably separated, with a mean classifier *AUC* of 62.77 % ($SD$ = 3.81, see Figure 9b). The individuals' best masks formed four clusters: one of bigger masks, including frontal and

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temporal regions (5 subjects) another of just frontal regions (5 subjects), one of temporal regions (7), and one of parietal regions (3).

Just as in the young adults, elaboration had no behavioral effect on WM, but in contrast to the young adults, the older adults also showed no benefit of elaboration on LTM. An individual's classifier *AUC* score was unrelated to WM performance, measured either by the *elaboration-minus-repeat benefit* ($r$ = -0.13, $p$ = 0.595), or by the *elaboration processing benefit* ($r$ = 0.34, $p$ = .146). There was also no significant correlation to LTM performance, indicated by the same contrasts (*elaboration-minus-repeat benefit*: $r$ = -0.27, $p$ = .244 and *elaboration processing benefit*): $r$ = -0.15, $p$ = .53).

## Discussion

The goal of the present study was to investigate to what extent elaboration and refreshing are separable processes, given prior reports of their neural overlap as well as their similar proposed roles for WM and LTM. We aimed at investigating whether refreshing and elaboration are distinct in their contribution to WM and LTM formation, whether they elicit separable neural activation patterns in fMRI, and how they relate to age-related memory deficits. We compared the neural and behavioral results of these processes to a control condition of re-reading (repeating) the words during the delay-period of a WM task. In the following, we discuss the effects of refreshing and elaboration on WM and LTM, as compared to repeating, and we argue that these processes are distinct and have distinct consequences on memory performance in young and old adults.

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**How does refreshing affect WM and LTM?**

We replicated the behavioral findings from Bartsch et al. (2018) that repeating items benefited WM performance more than refreshing did. This relative advantage was reduced when the neural processes of reading and refreshing were more similar. That is, refreshing benefited WM the most when it appeared, in the brain, to be most like the process of re-reading the memory items. This finding contributes to the current debate of *which* aspect of a word's representation is being reactivated by refreshing: Our results indicate that it is beneficial to refresh the visual perceptual trace of the word or the lexical representation that is elicited also by reading, with these characteristics forming a part of its multi-faceted representation in WM (D'Esposito & Postle, 2015; Eriksson et al., 2015; Lewis-Peacock & Postle, 2008; Ranganath, 2006; Ranganath & Blumenfeld, 2005; Ranganath et al., 2005).

The assumption that successful refreshing primarily re-activates the visual aspects of word representations converges with recent behavioral findings suggesting that thinking of an item in a perceptual/visual manner could result in a larger refreshing benefit: Souza, Vergauwe, and Oberauer et al. ( 2018) presented cues to refresh memory items during the retention intervals of various WM tasks to instruct people to refresh the cued items. The frequency of refreshing each item increased memory performance for both verbal and visual-spatial stimuli, but the benefits of refreshing were larger for visual–spatial than verbal materials. Hence, although refreshing is conceptualized as a domain-general mechanism, it might be optimized for the visuospatial system.

Another explanation for the reduced neural discriminability of re-reading vs. refreshing for those individuals with larger *refresh processing benefits* could be that the memory benefit arises from another process altogether, one that may be performed similarly during re-reading

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and refreshing: the strengthening of retrieval cues to the target information (Lewandowsky & Farrell, 2008; Oberauer & Hein, 2012; Oberauer & Lewandowsky, 2011). Accordingly, successful refreshers could be strengthening the content-context bindings in the refreshing condition in a similar way as on repeat trials in which they can explicitly re-encode the information. The current results cannot distinguish between these two interpretations. Nevertheless, what our results demonstrate is that successful refreshers perform this operation more similarly, and with similar behavioral advantages, as when they are afforded an opportunity to re-read the physical stimuli prior to the memory test.

**How does elaboration affect WM and LTM?**

The elaboration process can be distinguished from mere re-reading by the accompanying distributed patterns of fMRI activity in the brain. Whereas elaboration showed no benefit for WM, it did facilitate LTM performance for young but not old adults. Accordingly, in young but not old adults, the degree of neural separability of re-reading vs. elaboration was positively correlated with the elaboration benefit in LTM: Greater separation between the neural processes of reading and elaboration was associated with larger LTM benefits of elaboration across subjects (Figure *6* C & D). The present results confirm prior studies showing evidence against a WM benefit of elaboration (Loaiza & Camos, 2016). However, our findings fail to provide experimental support for the conclusion from previous studies which found that higher WM performance on complex-span tasks was correlated with individuals' use of elaboration strategies such as imagery and sentence generation (Bailey, Dunlosky, & Hertzog, 2009; Bailey et al., 2008, 2011; Dunlosky & Kane, 2007). This discrepancy could be due to the present study using a simple-span paradigm and previous research relying on complex-span tasks. Alternatively, the

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correlation might not reflect a causal effect of elaboration on memory – rather, participants who have good memory have more information in memory to elaborate on.

**Are refreshing and elaboration distinct processes?**

If refreshing and elaboration are two labels for the same process, then the pattern of behavioral effects should be the same for WM and on LTM, and the patterns of brain activity supporting these processes should be indistinguishable. In the present study, in a combined mask of a priori brain regions from frontal, temporal, and parietal lobes, we found successful differentiation of brain activity associated with re-reading, refreshing and elaboration processes. This neural evidence supports the assumption that refreshing and elaboration are implemented with distinct neural processes.

Further, as discussed separately above, refreshing and elaboration resulted in distinct behavioral effects on tests of WM and LTM. Replicating our previous work (Bartsch et al., 2018), we found that elaboration, but not refreshing, improves episodic LTM, but not WM. Taken together, the neural and behavioral results replicate and extend previous findings by supporting a distinction of the refreshing and elaboration processes.

**How do refreshing and elaboration contribute to age-related memory deficits?**

In addition to the question of whether refreshing and elaboration are distinct processes that can facilitate memory, another goal of the present study was to investigate whether these processes and their impacts on memory are preserved in older adults. As in our young adult sample, the three processes of repeating, refreshing, and elaboration were neurally distinguishable in the predefined mask of frontal, parietal and temporal regions for a majority of the older adults (N = 22 of 27; Figure 7). The direct comparison of repeating vs. refreshing

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provided confirmatory evidence that, like young adults, the older adults engaged these processes differently, and that individuals with a larger degree of neural separability also had larger behavioral benefits of repeating over refreshing. In young adults, the *refreshing processing benefit* also increased as the refreshing process became more similar to the repeating process in the brain. However, this relationship did not replicate for older adults. Instead, the *repeat processing benefit* was shown to decrease as these processes became more similar.

The interpretation we proposed for the young adults, of refreshing being most beneficial for memory when it appears in the brain to be like reading, does not appear to hold for older adults. Rather, our results indicate that refreshing is implemented differently, and less effectively, by older adults as compared to young adults. Future studies could account for these findings by, for example, instructing older adults to refresh an item specifically by "thinking of its visual representation". Such a manipulation would allow us to test whether implementing refreshing as a *simulated re-reading* of the memory items is most beneficial for WM, and it could also address whether a deficit in refreshing can be compensated for by teaching an effective strategy.

Similar to the young adults, refreshing had no benefit on LTM in older adults. This replicates the age-group specific findings of Johnson (2004), who also found no LTM benefit in old adults when comparing refreshing to re-reading. It was identified as an independent process, however, as refreshing was neurally separable from both re-reading and elaboration. As refreshing was not related to LTM performance, even in the young adults, we conclude that deficits in refreshing are not responsible for the LTM deficit in older adults either.

The results on elaboration show that the fMRI classifiers were able to differentiate mere re-reading from elaborating in the majority of the older adults (N = 20 out of 27; Figure 9). However, there was no LTM benefit of elaboration in older adults, whereas this effect was robust

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in the young group (Figure 2). We argue therefore that most of the older adults did perform some mental manipulation in the elaboration condition that was different from mere re-reading, but whatever it was did not affect their LTM performance. These results are in line with the *elaboration deficit hypothesis* (Smith, 1980), showing that when having to generate their own elaborations (here mental images), older adults do not benefit in the same way as young adults do. Taken together, our results provide evidence that the LTM deficit of older adults might arise at least in part from a deficit in the process of elaboration. Future research might investigate whether age-related LTM deficits can be compensated by providing more precise elaboration instructions.

**Conclusion**

Our study revealed that the processes of repeated reading, refreshing, and elaboration are differentiable in brain activation patterns in both young and older adults. Refreshing was most effective when its neural pattern resembled that of repeated reading, which indicates the importance of reinstating the perceptual state of memoranda that are no longer physically present. Elaboration as a process can be neurally distinguished from mere reading. While it had no impact on WM, elaboration did improve episodic LTM for young adults and the size of the benefit was related to the neural separability of elaboration: The more differentiated elaboration was from re-reading, the more elaboration benefited LTM. In contrast to the young adults, older adults' episodic LTM did not benefit from elaboration, even though this process was neurally separable from reading. This suggests that older adults implemented a sub-optimal form of elaboration, and this may be a contributing factor to age-related deficits in LTM.

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## Tables

*Table 1 ROIs with their corresponding BAs and references of previous reporting in univariate analyses in the literature.*

| Label | sub region | BA | Labeled region reported in |
|---|---|---|---|
| frontal | inferior frontal | 44,45,47 | Johnson et al., 2005; Johnson, Mitchell, Raye, & Greene, 2004; Raye, Johnson, Mitchell, Greene, & Johnson, 2007; Raye, Mitchell, Reeder, Greene, & Johnson, 2008 |
| | middle & superior frontal | 4,6, 8,9,10,46 | Blumenfeld, 2006; Blumenfeld, Parks, & Yonelinas, 2010; Kim & Giovanello, 2011; Murray & Ranganath, 2007 |
| parietal | | 3,7,40 | Johnson et al., 2004; Kim & Giovanello, 2011; Murray & Ranganath, 2007; Raye, Johnson, Mitchell, Reeder, & Greene, 2002; Raye et al., 2007, 2008 |
| fusiform | | 19, 37 | Murray & Ranganath, 2007; Raye et al., 2008 |
| parahippocampal | | 27, 28, 34, 35, 36 | Kim & Giovanello, 2011 Murray & Ranganath, 2007 |
| temporal | inferior | 20 | Blumenfeld et al., 2010; Johnson et al., 2004; Kim & Giovanello, 2011; Murray & Ranganath, 2007 |
| | middle | 21 | |
| | superior | 22, 38 | |

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Table 2 The posterior effect estimates and their 95% HDRs of the generalized linear mixed model for binomial response variables for the immediate serial memory data.

| | **mean parameter on probit scale** | **95% HDR** |
|---|---|---|
| (Intercept) | 0.09 | [-0.01, 0.19] |
| **processing** | **0.44** | **[0.38, 0.49]** |
| **repeat/refresh** | **-0.23** | **[-0.26, -0.19]** |
| elaboration | 0.01 | [-0.03, 0.05] |
| **age** | **-0.29** | **[-0.44, -0.15]** |
| **processing * repeat/refresh** | **-0.30** | **[-0.35, -0.26]** |
| processing * elaboration | -0.04 | [-0.08, 0.01] |
| repeat/refresh * elaboration | -0.02 | [-0.07, 0.02] |
| age * processing | 0.01 | [-0.07, 0.08] |
| **age * repeat/refresh** | **0.09** | **[0.04, 0.14]** |
| age * elaboration | 0.05 | [0.00, 0.10] |
| processing * repeat/refresh * elaboration | 0.02 | [-0.02, 0.08] |
| processing * repeat/refresh * age | -0.05 | [-0.11, 0.02] |
| processing * elaboration * age | 0.02 | [-0.05, 0.08] |
| repeat/refresh * elaboration * age | -0.06 | [-0.12, 0.00] |
| processing * repeat/refresh * elaboration * age | 0.00 | [-0.09, 0.08] |

*Note*. Credible effects, defined as HDRs excluding zero, are printed in bold.

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Table 3 The posterior effect estimates and their 95 % HDRs of the generalized linear mixed model for binomial response variables for the delayed memory data.

| | **mean parameter on probit scale** | **95% HDR** |
|---|---|---|
| **(Intercept)** | **-0.29** | **[-0.38 -0.25]** |
| **processing** | **0.06** | **[0.01, 0.1]** |
| **repeat/refresh** | **-0.05** | **[-0.09, -0.01]** |
| elaboration | -0.04 | [-0.09, 0] |
| **age** | **-0.06** | **[-0.11, -0.01]** |
| processing * repeat/refresh | -0.04 | [-0.09, 0.02] |
| processing * elaboration | -0.01 | [-0.07, 0.05] |
| repeat/refresh * elaboration | 0.05 | [-0.01, 0.11] |
| age * processing | 0.03 | [-0.03, 0.09] |
| age * repeat/refresh | -0.05 | [-0.11, 0.01] |
| **age * elaboration** | **0.08** | **[0.01, 0.14]** |
| processing * repeat/refresh * elaboration | -0.03 | [-0.12, 0.05] |
| processing * repeat/refresh * age | 0.05 | [-0.03, 0.14] |
| processing * elaboration * age | 0.05 | [-0.04, 0.13] |
| repeat/refresh * elaboration * age | -0.04 | [-0.13, 0.05] |
| processing * repeat/refresh * elaboration * age | -0.04 | [-0.15, 0.08] |

*Note*. Credible effects, defined as HDRs excluding zero, are printed in bold.

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# Figures

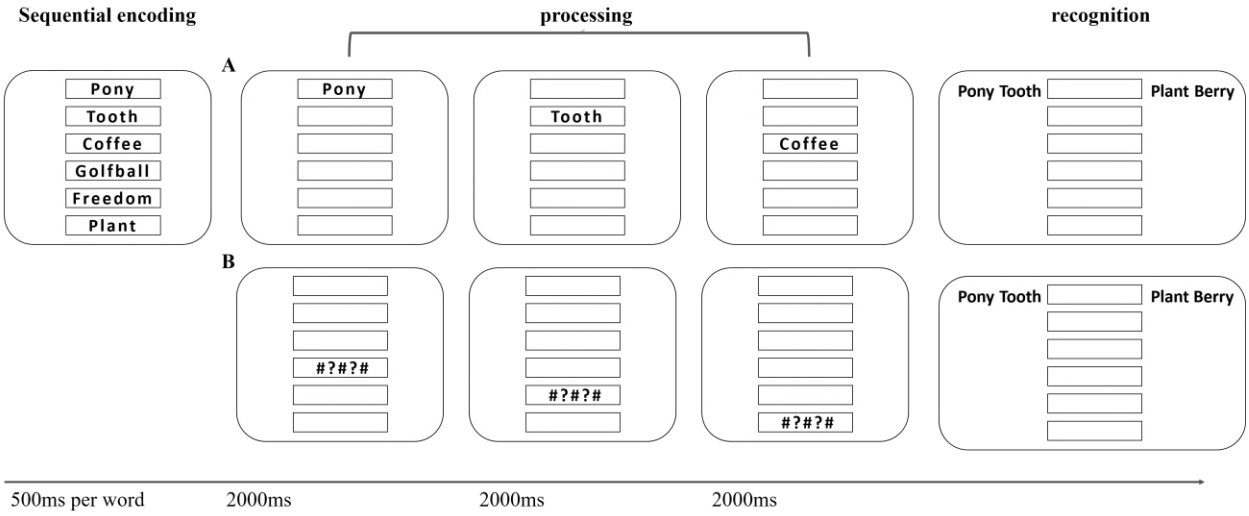


Figure 1. Illustration of the immediate memory paradigm. Subjects were shown a list of six words sequentially, followed by either the first (A) or second (B) triplet being processed according to the four experimental conditions. The trial ended with a recognition test in which each list item was tested in their order of presentation using a 4-alternative forced-choice procedure. (A) shows the repeat condition, which was preceded with the instruction to form a mental image in the elaboration condition. (B) shows the refresh condition, which was preceded with the instruction to form a mental image in the 4$^{th}$ condition (refreshing with elaboration).

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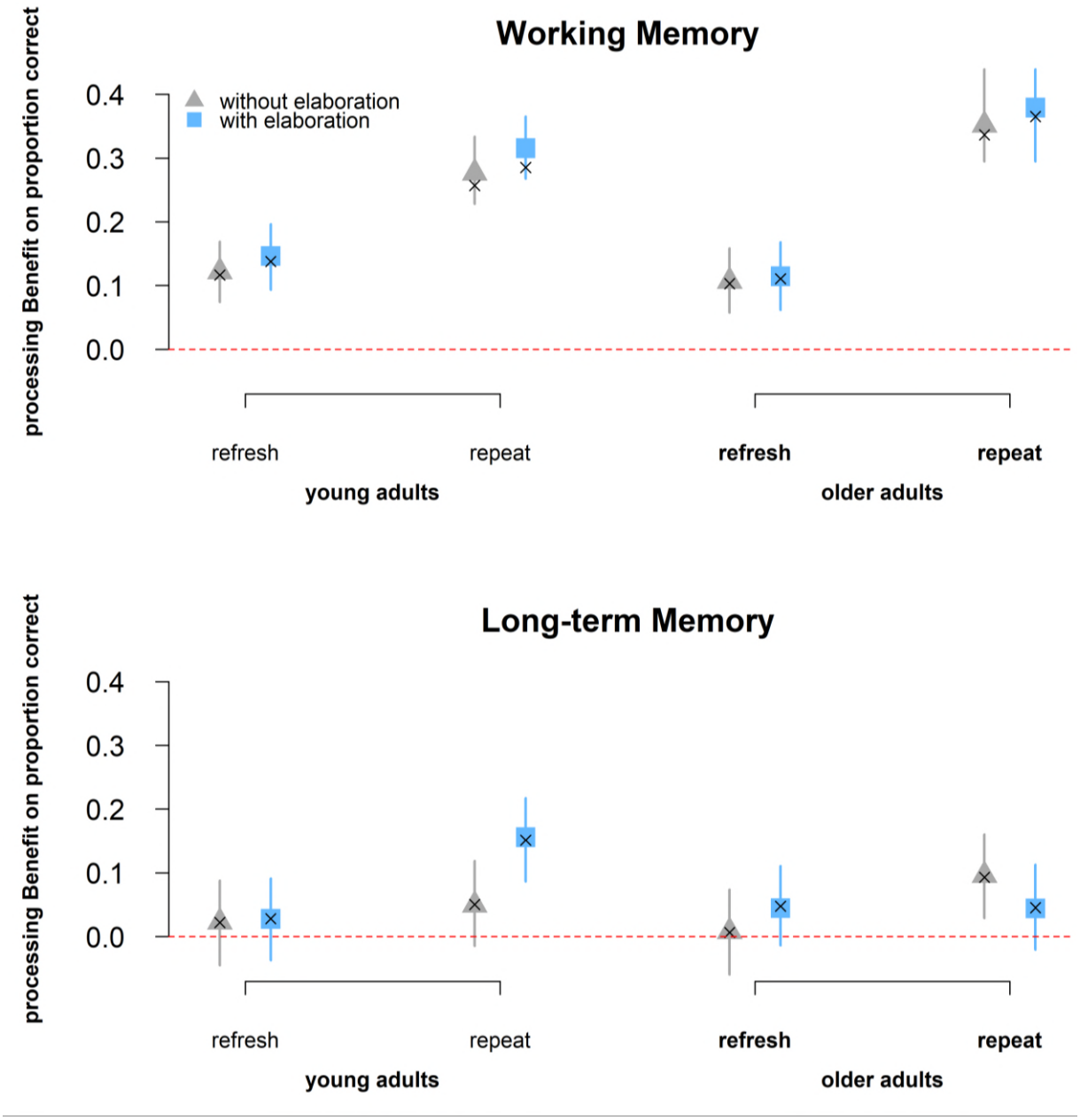


Figure 2 processing benefit in the WM (upper graph) and LTM (lower graph) task. The blue symbols and error bars represent estimated processing benefits and their 95% HDRs from the BGLMM for the conditions with elaboration, the grey symbols represent the same for the ones without elaboration. The crosses represent the observed data. Their overlap indicates that the model adequately describes the data. The red line represents the point of no difference in performance between the processed and the unprocessed triplet.

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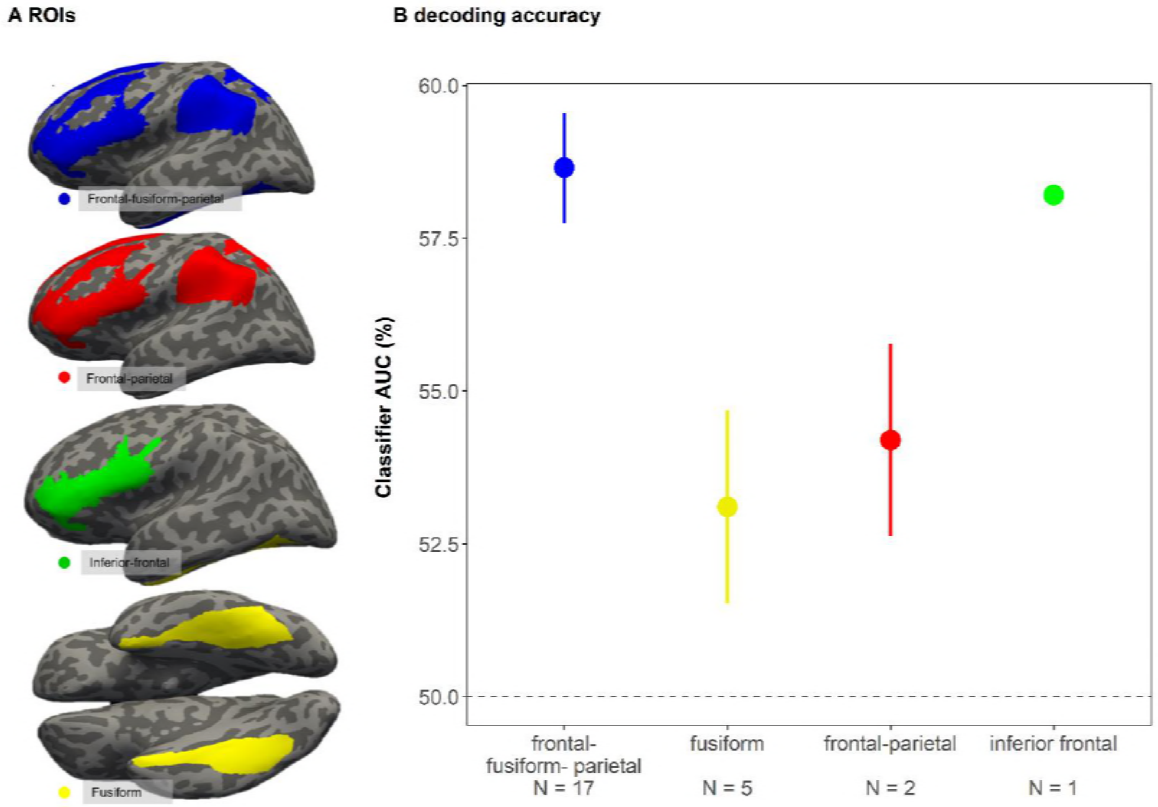


Figure 3 Classifier decodability across ROIs for Repeat vs. Refreshing vs. Elaboration in young adults. A: ROIs used for analysis. B: Decoding as indicated by the classifier AUC for the subjects in the frontal fusiform parietal mask or its subsets. The error bars indicate the standard error.

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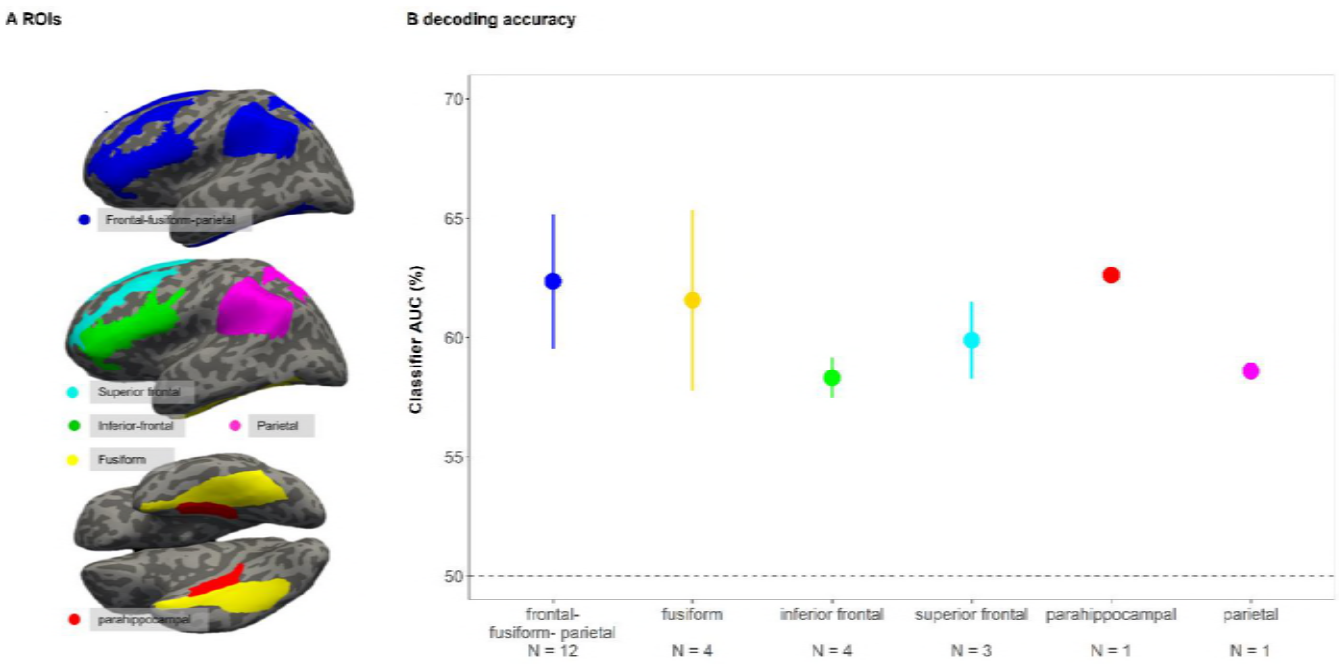


Figure 4 Classifier decodability across ROIs for Repeat vs. Refreshing for young adults. A: ROIs used for analysis. B: Decoding as indicated by the classifier AUC for each the subjects in the frontal fusiform parietal mask or its subsets. The error bars indicate the standard error.

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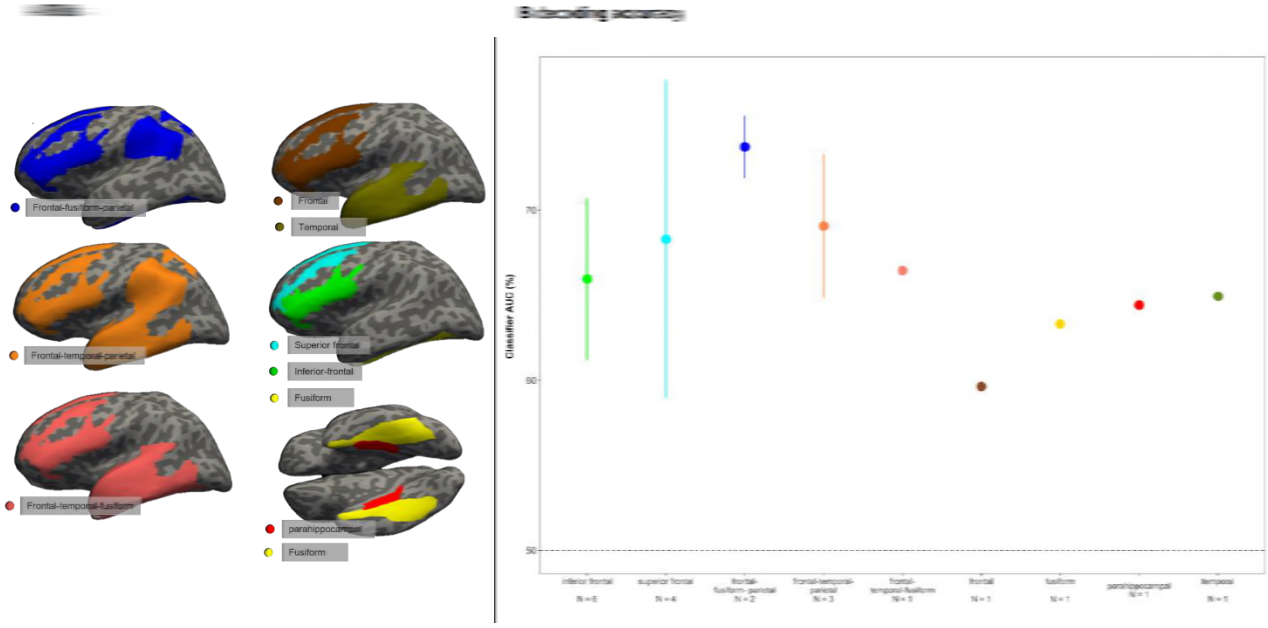


Figure 5 Classifier decodability across ROIs for Repeat vs. Elaboration for young adults. A: ROIs used for analysis. B: Decoding as indicated by the classifier AUC for each the subject in the frontal fusiform parietal mask or its subsets. The error bars indicate the standard error.

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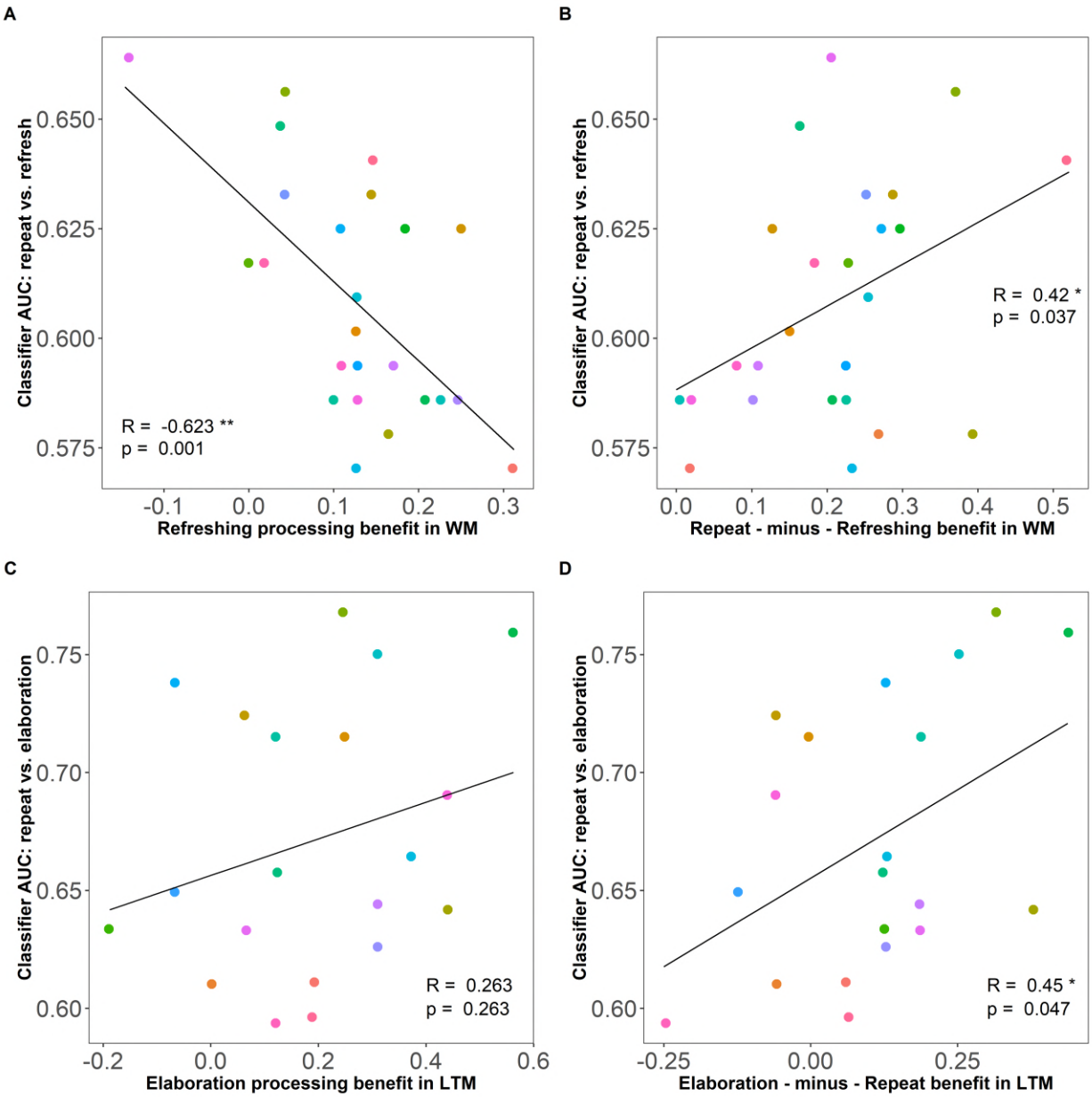


Figure 6 Correlation of MVPA classification (i.e. AUC) to memory performance. A: for the two-way problem of **Repeat vs. Refresh** in young adults to the subjects' behavioral refreshing processing benefit in working memory and to B: the subjects' behavioral repeat vs. refreshing benefit in working memory. Correlation of Classifier AUC for the two-way problem of **Repeat vs. Elaboration** C: to the subjects' behavioral elaboration vs. repeat benefit in long-term memory and D: to the subjects' behavioral elaboration vs. repeat benefit in long-term memory. Each point represents an individual subject.

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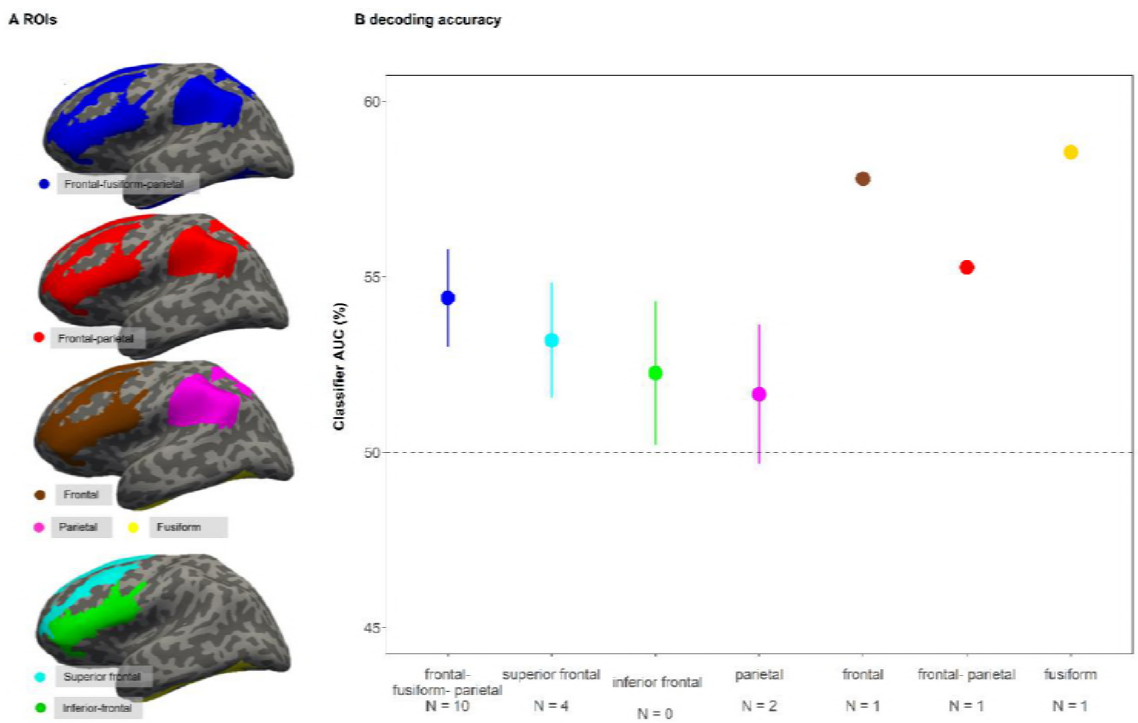


Figure 7 Classifier decodability across ROIs for the three-way problem Repeat vs. Refreshing vs. Elaboration in Older adults. A: ROIs used for analysis. B: Decoding as indicated by the classifier AUC for each the subjects in the frontal fusiform parietal mask or its subsets. The error bars indicate the standard error.

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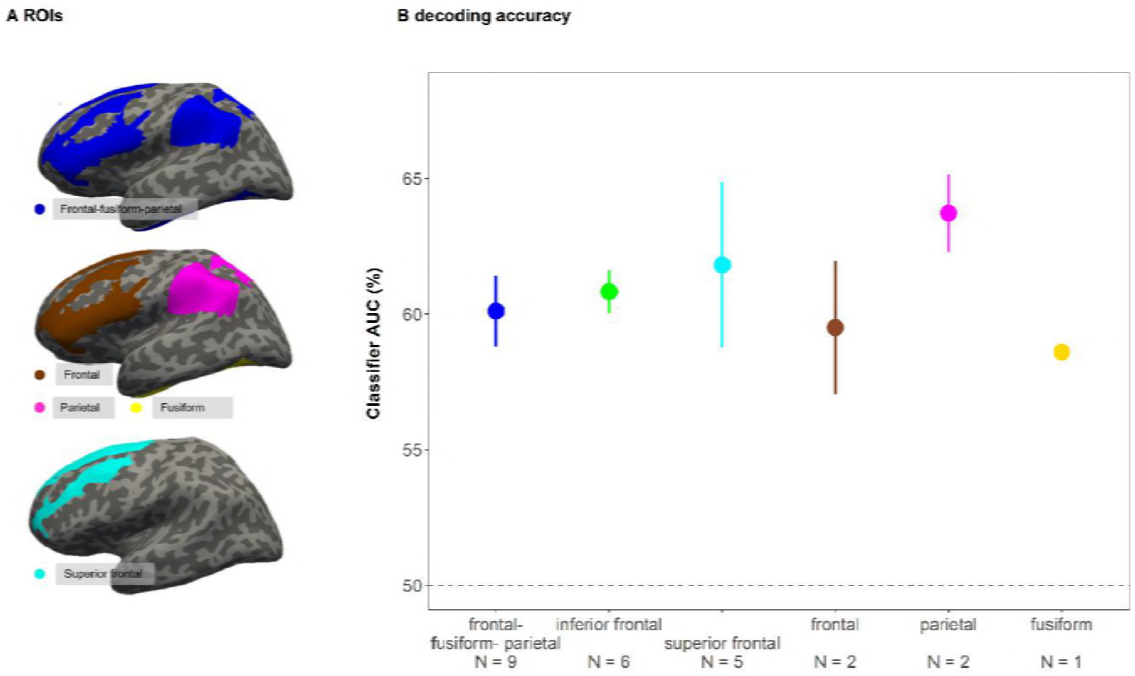


Figure 8 Classifier decodability across ROIs for Repeat vs. Refreshing in older adults. A: ROIs used for analysis. B: Decoding as indicated by the classifier AUC for each the subjects in the frontal fusiform parietal mask or its subsets. The error bars indicate the standard error.

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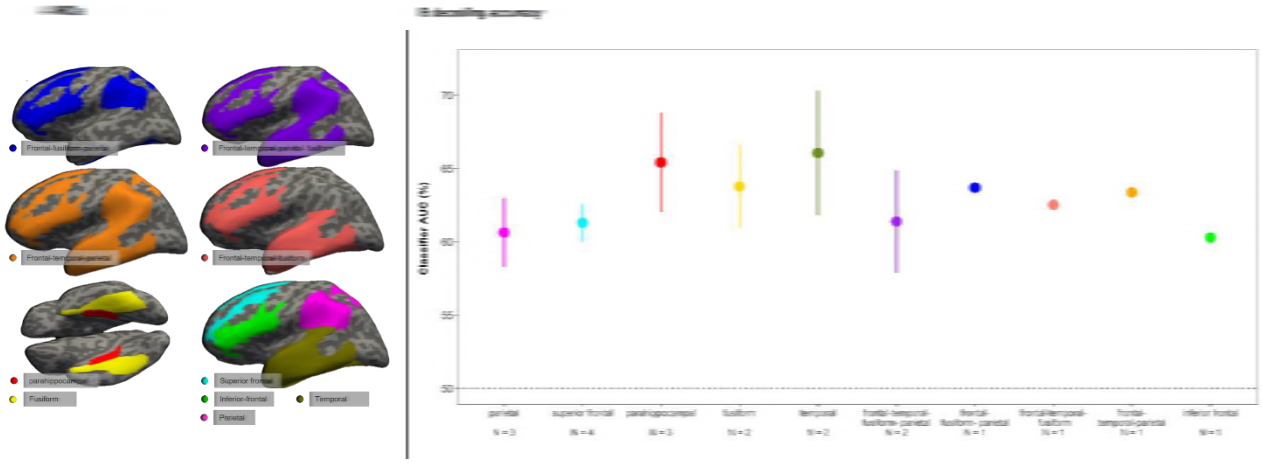


Figure 9 Classifier decodability across ROIs for Repeat vs. Elaboration in older adults. A: ROIs used for analysis. B: Decoding as indicated by the classifier AUC for each the subjects in the frontal fusiform parietal mask or its subsets. The error bars indicate the standard error.

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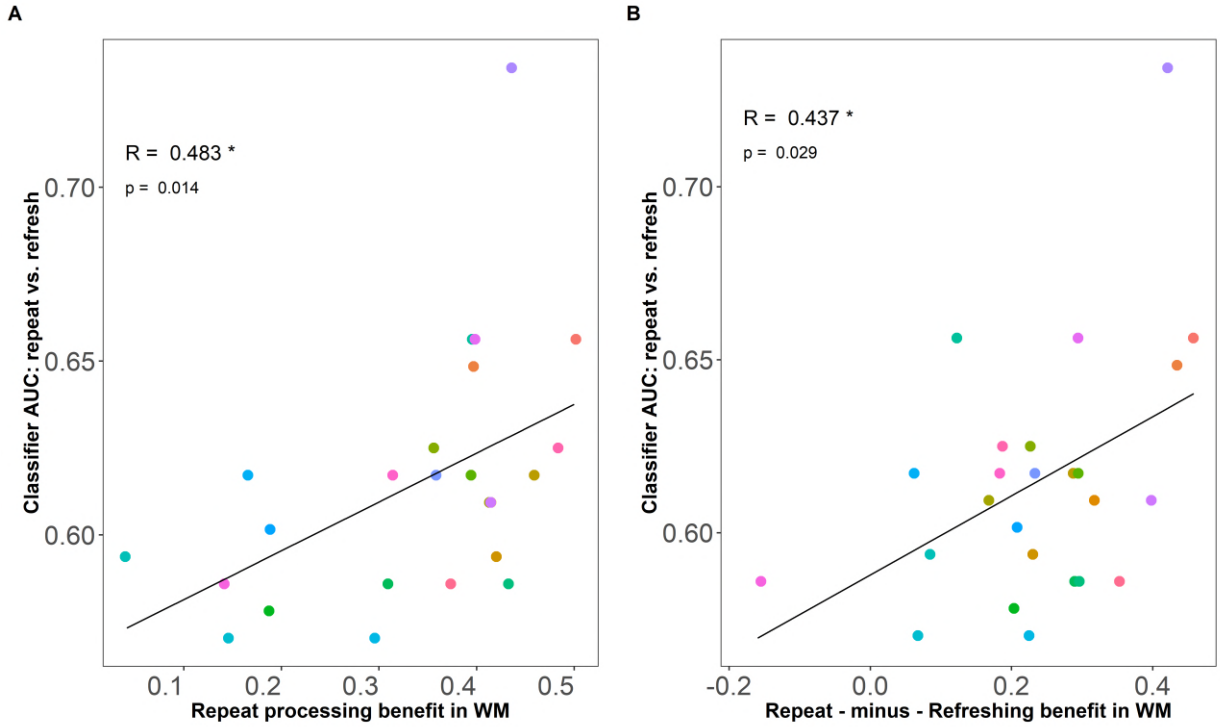


Figure 10 Correlation of MVPA classification (i.e. AUC) for the two-way problem of Repeat vs. Refresh in older adults to memory performance A: the subjects' behavioral repeat vs. refreshing benefit in working memory and B: the subjects' behavioral repeat processing benefit in working memory. Each point represents an individual.