



# Brain regions supporting retrieval of words drawn at encoding: fMRI evidence for multimodal reactivation

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## Abstract

Memory for words that are drawn or sketched by the participant, rather than written, during encoding is typically superior. While this *drawing benefit* has been reliably demonstrated in recent years, there has yet to be an investigation of its neural basis. Here, we asked participants to either create drawings, repeatedly write, or list physical characteristics depicting each target word during encoding. Participants then completed a recognition memory test for target words while undergoing functional magnetic resonance imaging (fMRI). Behavioural results showed memory was significantly higher for words drawn than written, replicating the typical drawing effect. Memory for words whose physical characteristics were listed at encoding was also higher than for those written repeatedly, but lower than for those drawn. Voxel-wise analyses of fMRI data revealed two distributed sets of brain regions more active for items drawn relative to written, the left angular gyrus (BA 39) and bilateral frontal (BA 10) regions, suggesting integration and self-referential processing during retrieval of drawn words. Brain-behaviour correlation analyses showed that the size of one's memory benefit for words drawn relative to written at encoding was positively correlated with activation in brain regions linked to visual representation and imagery (BA 17 and cuneus) and motor planning (premotor and supplementary motor areas; BA 6). This study suggests that drawing benefits memory by coactivating multiple sensory traces. Target words drawn during encoding are subsequently remembered by re-engaging visual, motoric, and semantic representations.

**Keywords** Drawing effect · fMRI · Encoding technique · Memory · Neuroimaging

## Introduction

Researchers have long been interested in documenting the effectiveness of various encoding techniques in influencing recall of to-be-remembered information. Numerous studies have demonstrated enhancements in episodic memory performance from techniques such as deep level of processing ( Craik & Lockhart, 1972), generation (Slamecka & Graf, 1978), enactment (Engelkamp & Krumnacker, 1980), and production (MacLeod et al., 2010), to name a few. These all reliably increase the amount of information that individuals can later recall, in comparison with more passive encoding

strategies such as reading or even writing out to-be-remembered information.

Drawing is another means of encoding information, and it has since been shown to enhance memory for words in younger (Meade et al., 2019; Wammes et al., 2016, 2017, 2019, Wammes, Meade et al., 2018a, Wammes, Roberts et al., 2018b) and cognitively healthy older adults (Meade et al., 2018), as well as those with probable dementia (Meade et al., 2020). Specifically, when asked to encode common nouns by either drawing a picture or writing out the word, both younger and older adults demonstrate superior recall and recognition performance for drawn information. Past work has also demonstrated that drawing a sketch, compared to writing during encoding, improves memory of to-be-remembered pictures (Wammes et al., 2016), academic terms (Wammes et al., 2017), and autobiographical events (Tran et al., 2022). One account of this effect is that drawing during encoding promotes the integration of various means of representing information: pictorial, motoric, and semantic (Wammes et al., 2019).

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Such an account for the drawing benefit incorporates aspects of the dual-coding theory put forth by Paivio (1971) to explain the well-known picture superiority effect – the finding of better memory for information when it is presented in picture than word format. Paivio (1971) theorized that pictures are likely processed visually, in terms of the image, as well as verbally, in terms of the label automatically given to the image when it is viewed. It is the dual nature of such representations, verbal and visual, that is believed to confer the memorial benefit documented for pictorial information. This explanation highlights that encoding techniques promoting incorporation of additional means of representation of to-be-remembered material can enhance later recall.

It has been suggested (Meade et al., 2019) that older adults benefit from drawing because this task incorporates elements of encoding techniques that are known to enhance memory in this population, namely semantic generation ( Craik & McDowd, 1987), inclusion of pictorial information (Ally et al., 2008; Cherry et al., 2012; Luo et al., 2007; Luo & Craik, 2008; Skinner & Fernandes, 2009; Winograd et al., 1982), and motoric enactment (Feyereisen, 2009). The finding that information presented in picture format is better remembered in older adults and those with probable dementia provides insight into how, from a neural perspective, drawing might be conferring a benefit to memory. As dementia of the Alzheimer's type progresses, neurons in the hippocampus and entorhinal cortex within the medial temporal lobes atrophy and lose efficiency due to accumulation of plaques and tangles (Gómez-Isla et al., 1996). In contrast, the primary visual areas and ventral visual pathway remain relatively intact, at least until more severe stages of the disease (Braak & Braak, 1991). In line with this, fMRI studies have demonstrated that while individuals with dementia exhibit poorer activation within the medial temporal lobes during visual memory tasks, the activation patterns in occipital regions remain similar to healthy controls (Golby et al., 2005; Koenig et al., 2008). Given this, one account for why drawing is so beneficial to memory, even in patients with dementia, is that it relies on the relatively preserved posterior regions of the brain involved in visual perceptual processing to mediate performance (Meade et al., 2020). This account is similar to an explanation put forward to explain why the picture superiority effect is also preserved in such populations (Ally, 2012; Ally et al., 2008; Ally & Budson, 2007).

It seems likely that reliance on visuo-perceptual representations is a key factor underlying the benefit of drawing to memory. Indeed, recent fMRI studies have demonstrated that drawing, as a complex visuomotor activity, evokes neural activity in V1 and V2 as well as the lateral occipital cortex, parietal sites, pre-central gyrus, and motor regions (Fan et al., 2020; Vinci-Booher et al., 2019). Drawing has also been associated with broader activation of the cerebellum,

somatosensory regions, frontal regions, and the dorsal visual stream (Fan et al., 2020; Griffith & Bingman, 2020; Vinci-Booher et al., 2019). Thus, the neural basis of the drawing effect likely stems from the creation of a visuo-spatial representation of to-be-remembered information (i.e., a target word) that supplements a verbal one.

Behavioural studies, however, suggest that the drawing effect is not due simply to a picture superiority effect, as the benefit to memory is greater than that elicited by viewing target pictures or engaging in mental imagery during encoding (Wammes et al., 2019). Similarly, the drawing effect cannot be fully accounted for by engagement of a deeper level of processing (as in Craik & Lockhart, 1972) of materials at encoding, as the memory benefit is larger than when semantic elaborative processing is engaged at encoding (Wammes et al., 2017, 2019). Wammes and colleagues put forward a 'component-integration' account for the drawing effect. They suggest that drawing not only engages visual, semantic, and motoric processing during encoding, but that the act of drawing seamlessly integrates these traces. It is this multi-modal memory trace that allows for greater and more reliable performance on a subsequent retrieval test. The trace is more easily reactivated during retrieval, perhaps because there are multiple routes to remembering the information, or because its strength is overall greater compared to when information is encoded with fewer modes of representation.

## Memory reactivation

There is evidence to suggest that the patterns of brain activity engaged during encoding will become re-activated again when remembering that experience. In fact, a feature of vivid remembering is the reactivation of the same cortical areas engaged during the initial perception of an encoded stimulus (Buckner et al., 2001). In general, memory retrieval is believed to be accompanied by similar sensory-specific cortical activation as that produced during the initial encoding of an item or event (Norman & O'Reilly, 2003; Rubin & Greenberg, 1998; Woodruff et al., 2005). For example, studies in which participants associate words with pictures, sounds, or faces during encoding and are subsequently asked to make memory decisions to only the word stimulus, have found that secondary visual, secondary auditory, and face processing regions of the brain are activated during retrieval, depending on which stimulus was associated with the word during encoding (Khader et al., 2005; Nyberg et al., 2000; Vaidya et al., 2002; Wheeler et al., 2000).

Here we aimed to determine the neural processing that supports retrieval of memories for words that were drawn, written, or semantically elaborated upon during encoding. In so doing we can not only specify the neural basis of the drawing effect during memory retrieval, but also examine whether there is neural support for the idea that drawing

engages multiple forms of representation. A similar logic was applied in other studies. For example, studying pictures results in subsequent reactivation of occipital regions involved in visual perceptual processing even when the retrieval test presents these targets as words (Vaidya et al., 2002). Along the same lines, encoding information using enactment (engaging in physical movement that depicts the to-be-remembered information during encoding) results in reactivation of motor processing regions during subsequent retrieval of enacted words (Krönke et al., 2013; Macedonia & Mueller, 2016; Mayer et al., 2015; Roberts et al., 2022). A similar principle can also be seen during retrieval of information initially encoded using semantic elaboration. During retrieval, neural activation is higher in inferior frontal regions implicated in semantic processing compared to when information is encoded more shallowly (Otten et al., 2001; Poldrack et al., 1999; Staresina et al., 2009; Wagner et al., 1998). As such, examining neural activation at the time of retrieval should illuminate the processing involved in encoding and representing drawn information in memory.

### Current study

In the current study we aimed to determine what neural activity supports memory for drawn information relative to words encoded by writing or semantic elaboration (listing descriptive characteristics pertaining to the to-be-remembered word). We asked participants to encode words outside of the scanner, and to later make recognition memory decisions to words presented while their brains were scanned using functional magnetic resonance imaging (fMRI).

We expected that recognizing drawn words would recruit brain regions involved in visual, motor, and semantic processing to a greater extent than when making memory decisions to words that were written or those for which physical characteristics were listed at encoding. We also expected greater activity following drawing in the bilateral extrastriate visual cortex, namely fusiform, lingual, middle occipital, and inferior temporal gyri, based on previous work examining memory for pictures relative to words (Vaidya et al., 2002).

Given that complex motor plans would be required by drawing during encoding, we expected to observe activity in the primary motor cortex and sensorimotor networks (such as the supplementary motor area; SMA) during later retrieval, as these areas have been linked to memory following enactment of actions (Krönke et al., 2013; Macedonia & Mueller, 2016; Macedonia et al., 2011; Straube et al., 2009). We also reasoned that words written or described physically at encoding might engage these regions as well because all three tasks require physical motor control of a pencil. The motor processing engaged while drawing, however, is

arguably more unique than for writing, and as such may engage additional supplementary motor regions involved in meaningful motoric elaboration (Macedonia et al., 2011; Straube et al., 2009). Given that semantic processing may be engaged when planning or elaborating on an image to be drawn during encoding, we reasoned that activity may be greater in inferior frontal and medial temporal regions, posterior parahippocampal gyrus (Brewer et al., 1998; Wagner et al., 1998), and left medial temporal lobe (Köhler et al., 2000), which have been found to be recruited for deep semantic, relative to shallow, processing.

## Method

### Participants

Of the recent studies that explored the benefit of drawing at encoding on recognition memory, the smallest effect size (memory for draw > write) was  $d = 0.67$  (Wammes et al., 2016, Experiment 5). We therefore performed a power analysis (matched-pairs, two-tailed,  $\alpha = .05$ ,  $d = 0.67$ ) using the *pwr* package (v. 1.3.0; Champley et al., 2020) for *R* (R Core Team, 2020), which indicated a required sample size of 20 participants to achieve 80% statistical power.

A total of 20 (16 female;  $M$  age = 22 years,  $SD$  age = 2.31) undergraduate students were recruited through email invitation and poster advertisements at the University of Waterloo. All participants met with the researcher on campus in advance of their study participation date to receive detailed information about the study procedure and to complete an MRI checklist to ensure eligibility for scanning prior to participating. On the day of the study, participants gave written informed consent prior to their participation, and were remunerated \$25 CAD following the study. One additional participant took part in the study but their data were not analyzed due to experimenter error leading to a loss of data.

### Materials

#### Word list

Ninety words were selected from the verbal labels for Snodgrass images (Snodgrass & Vanderwart, 1980) to ensure that all words could be readily drawn. Words ranged in frequency from 2.48 to 6.01 ( $M = 4.14$ ,  $SD = 0.61$ ) using the *wordfreq* Python library (Speer et al., 2018), in length from three to 12 letters, ( $M = 5.5$ ,  $SD = 1.19$ ), and in number of syllables from one to four ( $M = 1.64$ ,  $SD = 0.83$ ). All words were common nouns of objects deemed by the

researchers to be highly familiar and prevalent in everyday life (e.g., table, apple, bird).

### Paper and pencil materials

Each participant completed the drawing, writing, and listing encoding tasks using a 4-in. × 6-in. pad of paper and a pencil.

### Tone identification task

Sound files representing low-, medium- and high-pitched tones were created using Audacity software (Audacity Team, 2021), such that each sine wave tone was exactly 500 ms in duration, at frequencies of 350, 500, and 650 Hz, respectively. This tone identification task was used as a filler task in between encoding and the recognition test, matching prior work on the drawing effect (e.g., Wammes et al., 2016).

### Neuropsychological evaluations

**Mill Hill Vocabulary Scale** Participants were administered set B of the Mill Hill Vocabulary Scale (Raven et al., 1976), in which one must select the correct synonym from a set of six alternatives. On average, participants responded correctly to 54% ( $SD = 12%$ ; range 30% to 79%) of the items, indicating fluency in the English language (Raven et al., 1976).

**NART** The National Adult Reading Test (NART; Nelson, 1982) was used to provide an estimate of intelligence. The NART consists of a 50-item list of irregularly pronounced English words, which participants read aloud. On average, participants correctly pronounced 62% ( $SD = 16%$ ) of the words, indicating IQ scores within a typical range (defined as NART scores above or around 50%; Bright et al., 2018).

### Program and presentation equipment

Stimulus presentation during encoding was accomplished using E-Prime software (v. 3.0.3.60; Psychology Software Tools, 2016) presented on a Windows laptop. The stimuli in the retrieval task were presented using an Avotec Silent Vision (Model SV-7021) fiber-optic visual presentation system with binocular projection glasses controlled by a computer running E-Prime software synchronized to trigger-pulses from the magnet. Responses on the recognition test were made with participants' right index and middle finger using a Lumina SRB Model 200A MRI response pad with SRBox input to E-Prime.

### Procedure

The entirety of the study took place at Grand River Hospital, located in Kitchener, Ontario. A small side room next to the MRI suite was used for the initial encoding tasks, as well as for completion of neuropsychological questionnaires and debriefing following the scanning session. The procedures and materials for this study were approved by the Office of Research Ethics at the University of Waterloo and the Tri-Hospital Research Ethics Board at Grand River Hospital. All data, analysis code, experiment programs, and other materials are listed on the Open Science Framework (OSF; <https://osf.io/74mdc/>).

### fMRI scanning parameters

At the beginning of the scanning session, a whole-brain T1-weighted anatomical image was collected for each participant (TR = 7.5 ms; TE = 3.4 ms; voxel size,  $1 \times 1 \times 1 \text{ mm}^3$ ; FOV =  $240 \times 240 \text{ mm}^2$ ; 150 slices; no gap; flip angle = 8 degrees). Each recognition test run was scanned using an event-related design. Functional data were collected using gradient echo-planar T2\*-weighted images acquired on a Philips 1.5 Tesla machine (TR = 2000 ms; TE = 30 ms; slice thickness = 5 mm with no gap, 26 slices; FOV =  $200 \times 200 \text{ mm}^2$ ; voxel size =  $2.75 \times 2.75 \times 5 \text{ mm}^3$ ; flip angle = 70 degrees). Each of the six experimental runs took 120 s to complete and had 26 slices per volume, 60 volumes total, consisting of five target words from each encoding task (15 total), 15 lure words, and 19–24 fixation-cross baseline trials (the number of fixation crosses varied due to their random presentation times of 1–6 s). Before each experimental run began, there was an 8-s steady-state time whereby a fixation cross was presented but no functional data were recorded.

### Encoding phase

The encoding phase was completed outside of the scanner, while the participant was seated in a chair, at a table. Prior to beginning, participants gave informed signed consent. At the beginning of the encoding phase, participants completed a brief practice session to familiarize them with the encoding and retrieval tasks and were encouraged to ask questions for clarification. Practice consisted of three encoding trials, one for each condition, followed by a six-item old-new recognition test; none of the words in this practice phase were included in the experimental phase. The duration of the encoding phase was approximately 20 min including the practice session.

From the master stimuli list of 90 words, 30 were randomly selected to be drawn, 30 written, and 30 listed, with

the presentation of the encoding trial types intermixed.<sup>1</sup> On each encoding trial, the prompt appeared in the center of the screen above the target word. Participants then had 10 s to perform either the drawing, writing, or listing task, depending on which was indicated by the prompt. A 500-ms tone alerted them to stop performing the task and prepare for the next target word and prompt. A blank screen was then presented for 4 s to give participants time to flip their sheet of paper to the next page before the next word and prompt appeared. Before the practice phase, participants were informed of the time constraints for each item and that they would hear a tone to indicate the end of the trial and the appearance of the ensuing prompt/target word for the next trial.

Participants were told that depending on the prompt presented during each individual trial, they were to either 'draw', 'write', or 'list' in response to the target word on the pad of paper provided. For the 'draw' prompt, participants were instructed to draw a picture illustrating the object that the word on the screen represents, and to continue adding detail for the full duration of the trial. For the 'write' prompt, participants were instructed to clearly and carefully write out the word multiple times. For the 'list' prompt, participants were instructed to write out a list of physical descriptive characteristics for the object the word represents, and were given the example that for 'mouse' they might list words like 'furry', 'grey', 'long tail', 'small', etc.

### Retention interval

Following the end of the encoding phase, participants immediately completed a 2-min tone classification filler task to prevent immediate rehearsal of encoded words. In this task, participants were presented three tones (350, 500, or 650 Hz), one at a time for 500 ms each, in a random order, and were asked to indicate via a button press whether it was a low-, medium-, or high-pitched tone. Afterwards, participants changed into MRI-compatible clothing, completed an MRI safety screening assessment form with the technician, and were situated on the MRI scanner bed. Fiber-optic binocular projection glasses were adjusted within the scanner to ensure that participants had a clear view of a sample word presented on the screen. An anatomical scan was then completed, lasting approximately 8 min. Following the anatomical scan, participants were again given instructions on the format of the recognition test, how they should make their

responses, and a reminder to limit their head movement as much as possible. The total duration of the retention period between the end of the encoding phase and the beginning of the recognition test was approximately 20 min.

### Retrieval phase

The recognition phase began once participants verbally indicated they were comfortable and understood the instructions. Word stimuli were presented through the binocular projection glasses, controlled by a computer running an E-Prime program. In total, the recognition test consisted of 180 words that were presented in an intermixed order, with 90 words from the encoding phase (30 drawn, 30 written, 30 listed) and 90 new/lure words. The recognition test was divided into six separate runs of equal length, each lasting 2 min in duration. Each run contained five words of each encoding type (drawn, written, and listed) and 15 lures, with each word presented for 2 s. Recognition response trials only progressed after 2 s had elapsed, and did so regardless of whether a key-press was made earlier. The onset of word presentation in each run was pseudo-randomized using OptSeq2 (Dale, 1999; Greve, 2006), a tool for automatically scheduling the order and timing of events for rapid-presentation event-related fMRI experiments. In addition to words, there were also fixation crosses presented in a random order, intermixed with the words. Fixation crosses were displayed for a random length of time between 1 and 6 s. To ensure a consistent neuroimaging scan time, the duration of fixation crosses in each run was determined by the number of fixation crosses presented, ranging from 19 to 24. Because fixation crosses were randomly dispersed throughout the retrieval phase, gaps between stimulus presentation ranged from 0 s in the case of back-to-back word presentations and 1–6 s if a fixation cross was presented in-between encoding words (the latter of which was much more frequently the case). There was a brief break between each run (maximum 30 s) during which the researcher asked the participant over a speaker if they were comfortable and ready to begin the next run. The total duration of the recognition test, including all six runs, was a maximum of 15 min.

Participants were instructed to respond as quickly and accurately as possible to each word presented on the screen by indicating if the word was 'old', meaning they saw it in the encoding phase, or 'new', meaning they did not see the word in the encoding phase. Responses were made using two buttons indicating either 'old' or 'new' on a Lumina MRI response pad. All responses were also manually recorded by the researcher on a sheet of paper as backup. Following completion of the recognition test runs, participants were brought back to the small side room and completed set B of the Mill Hill Vocabulary Scale and the NART with the researcher. Finally, they were debriefed, and given remuneration for their time.

<sup>1</sup> Due to experimenter error, we did not counterbalance the words assigned to each encoding task. However, there were no significant differences between the words in each encoding task in terms of frequency,  $F(3, 176) = 0.53$ ,  $p = .66$ , number of letters,  $F(3, 176) = 0.38$ ,  $p = .77$ , and proportion of words representing animate vs. inanimate objects,  $F(3, 176) = 0.88$ ,  $p = .45$ .

## fMRI data preprocessing and analyses

fMRI data were preprocessed and analyzed using AFNI software (v. 20.3.01; Cox, 1996). To begin, each subject's fMRI data were converted from raw DICOM files to seven separate three-dimensional (3D) datasets using the `to3d` command, with the first representing the anatomical volume and the latter six representing functional data. Each subject's anatomical image was then entered into AFNI's `@SSwarper` (v. 2.6; Cox, 2022; Saad et al., 2009) tool, which performed skull-stripping and non-linear alignment to the Talairach-Tournoux atlas template (TT\_N27\_SSW; Talairach & Tournoux, 1988). The results of this process were checked manually via automatically generated quality-control images provided by the program.

Next, data from each subject underwent a customized version of AFNI's `afni_proc.py` pipeline (v. 7.49; Taylor et al., 2018). It included slice timing alignment on volumes, alignment of functional data to the anatomical dataset, warping of anatomical data to Talairach standard space, volume registration, and whole-brain masking. Blurring was then performed using a 6-mm Gaussian blur with a full width at half maximum (FWHM) to increase the signal-to-noise ratio. Original anisotropic  $2.75 \times 2.75 \times 5 \text{ mm}^3$  voxels were resampled to isotropic  $2.75 \times 2.75 \times 2.75 \text{ mm}^3$  voxels with a volume of  $20.797 \text{ mm}^3$  each. Motion artefacts were detected and censored at a 0.3-mm cut-off and outlier datapoints were also censored at 5%. Each run of functional data was scaled to a mean of 100 before undergoing a regression analysis to build a model that included timing data from all four possible recognition test response outcomes: correct hits for target items, false alarms for lure items, correct rejections for lure items, and misses for target items. For two participants, neuroimaging data from a single functional run each were missing, but their remaining data were included in analyses.

After each participant's data had undergone this same preprocessing pipeline, all data were entered into a repeated-measures ANOVA using the `3dANOVA2` command (v. 23.0.00; Ward, 2023). In this ANOVA, only correct hits on old target items and correct rejections of lure items were considered. Contrasts were then conducted to compare each of the three target conditions. We also examined contrasts between hits in each condition and correct rejections of lure items (e.g., Draw – New). As a result, voxel-wise analyses were performed for trials in which correct recognition responses were made to items belonging to the Draw ( $M = 28$  hits), List ( $M = 26$  hits), Write ( $M = 16$  hits), or New ( $M = 83$  correct rejections) conditions.

Following the ANOVA, `3dmask_tool` was used to form an intersection mask that represents voxels that were persistent across at least 70% of participants. Next, to calculate the minimum number of voxels needed for cluster-size thresholding,

we used the `-ClustSim` option in `3dttest++` (Cox et al., 2017) for each individual contrast of interest. This modern non-parametric method of determining cluster thresholds uses a non-Gaussian spatial autocorrelation function (ACF) and runs 10,000 simulations to reveal a minimum number of voxels that would be needed for each cluster to achieve significance at the recommended  $p < .001$  level (Woo et al., 2014) while maintaining the false-positive rate at  $p < .05$  (Cox et al., 2017). The minimum number of voxels for significant cluster formations in each contrast varied from 9 to 33, and clusters were formed assuming bi-sided tests with  $NN = 2$ .

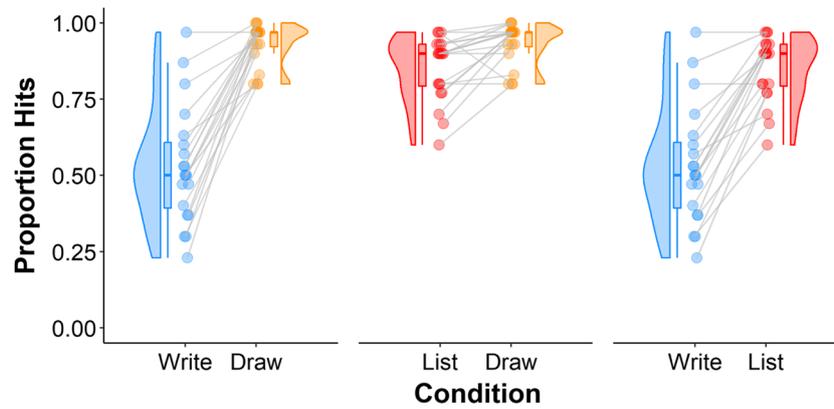
Finally, the `3dTcorr1D` command was used to calculate brain-behaviour Spearman rank correlation maps for each contrast (i.e., Draw vs. Write, Draw vs. List, and List vs. Write). In these analyses, the proportion of words correctly recognized in each condition was tabulated and subtracted from that of the other condition (e.g., Draw – Write). The value of each of these difference scores was then correlated with differences in brain activity for that specific contrast (e.g., Draw vs. Write). Finally, an aggregate group-level correlation map was formed across the whole brain. No brain-behaviour correlations survived when significance was set at  $p < .001$  with a minimum cluster-size threshold of 20 voxels. In the spirit of conducting exploratory analyses that can inform future investigations, the significance threshold was then lowered to  $p < .01$  while maintaining a 20-voxel minimum cluster-size.

In the voxel-wise and correlational analyses, significant clusters were localized to anatomical brain regions within 2 mm and 3 mm, respectively, of the peak voxel coordinate in the cluster, as determined by the Talairach Daemon atlas (Lancaster et al., 2000) through AFNI's `whereami` function. In Figs. 2 and 3, functional data are overlaid on a Talairached version of the Colin 27 anatomical dataset (i.e., the TT\_N27 template; Holmes et al., 1998). For fMRI images using transparent thresholding (Taylor et al., 2022), see our page on the OSF (<https://osf.io/74mdc/>).

## Results

### Behavioural memory performance

To examine memory performance across conditions, a one-way repeated-measures ANOVA was conducted using the `afex` package (v. 1.2-1; Singmann et al., 2023) for *R*, with Condition as the independent variable with three levels (Draw, List, and Write) and hit rate on the recognition test as the dependent measure. Mauchly's test indicated that the assumption of sphericity had been violated,  $W = 0.63$ ,  $p = .016$ ,  $\epsilon = .731$ , therefore a Greenhouse-Geisser correction was applied to the ANOVA. Results revealed a significant main effect of Condition,  $F(1.46, 27.79) = 74.40$ ,  $MSE = 0.02$ ,



**Fig. 1** Pairwise contrasts for recognition test hit rate. Hit rate memory performance is shown for each contrast of encoding conditions using smoothed distributions and box-plots. Individual data points for

each participant are also included, connected with a line to show the change in performance between two conditions

$p < .001$ ,  $\eta_p^2 = .80$ ,  $BF_{10} = 3.04e+10$ .<sup>2</sup> Paired-samples *t*-tests with Bonferroni adjustments showed that memory was higher in the Draw relative to both the Write condition,  $t(19) = 9.44$ ,  $p < .001$ ,  $d = 2.11$ ,  $CI_{95} [1.30, 2.90]$ ,  $BF_{10} = 9.66e+5$ , and the List condition,  $t(19) = 3.51$ ,  $p = .007$ ,  $d = 0.79$ ,  $CI_{95} [0.27, 1.28]$ ,  $BF_{10} = 17.54$  (see Fig. 1). Items from the List condition were also better recognized than those in the Write condition,  $t(19) = 8.95$ ,  $p < .001$ ,  $d = 2.00$ ,  $CI_{95} [1.22, 2.76]$ ,  $BF_{10} = 4.43e+5$  (see Table 1). In each case, large values for the Bayes factors indicate strong or extreme evidence in favor of the alternative model.

**fMRI results**

Using a significance threshold of  $p < .001$  while controlling family-wise error to  $p < .05$ , and with minimum cluster sizes set custom for each contrast (ranging from 9 to 33 voxels), brain activity was examined when correct memory responses were made to items belonging in the Draw, List, and Write conditions (see Table 2). Words from the Draw and List conditions elicited distinct neural activity from correct rejection responses to New items, while those from the Write condition did not lead to any significant clusters that survived thresholding.

When comparing brain activity for correctly recognized words from the Draw relative to Write encoding conditions,

**Table 1** Recognition test memory performance

Trial type	p('Old') Response		
	<i>M</i>	<i>SD</i>	95% CI
Write	.53	.19	[.44, .62]
List	.85	.11	[.80, .90]
Draw	.93	.07	[.90, .96]
New	.08	.09	[.04, .12]

Trial type 'new' refers to lure items on the recognition test. As such, p('old') for that category is the false alarm rate

significant clusters of positive activity peaked in the left and right medial frontal gyri and the left middle temporal gyrus (see Fig. 2). Activity for correctly recognized words from the List relative to Write condition was significantly higher in a single cluster that also peaked in the left middle temporal gyrus.

To assess whether differences in neural activation between conditions correlated with differences in behavioural memory performance outcomes, we calculated Spearman rank correlations for each contrast. Here, we focus on brain-behaviour correlations for our main contrast of interest: Draw – Write. Four distinct positive correlation clusters were determined to be significant, with peaks in the right inferior and superior frontal gyri, left cuneus (i.e., area V1), and left middle frontal gyrus (see Table 3).<sup>3</sup> Activity in the

<sup>2</sup> Bayes factors were calculated using the *BayesFactor* package (version 0.9.12-4.4; Morey et al., 2011) for R, enlisting a default Jeffreys-Zellner-Siow (JZS) prior with a Cauchy distribution (center = 0,  $r = 0.707$ ). This package compares the fit of various linear models. In the present case, Bayes factors for the alternative ( $BF_{10}$ ) are in comparison to intercept-only null models. Interpretations of Bayes factors follow the conventions of Lee and Wagenmakers (2013). Bayes factors in favor of the alternative ( $BF_{10}$ ) or null ( $BF_{01}$ ) models are presented in accordance with each preceding report of NHST analyses (i.e., based on a  $p < .05$  criterion) such that  $BF > 1$ .

<sup>3</sup> A leave-one-out cross-validation analysis confirmed that the effect sizes at the peak voxel coordinate in each cluster for the Draw – Write contrast were stable across 20 leave-one-out datasets and matched the effect sizes seen in the full data set, as reported in Table 3: inferior frontal gyrus (mean  $\rho = .80$ , 95% CI = [.79, .81]), superior frontal gyrus (mean  $\rho = .75$ , 95% CI = [.74, .76]), cuneus (mean  $\rho = .77$ , 95% CI = [.76, .78]), and middle frontal gyrus (mean  $\rho = .73$ , 95% CI = [.72, .75]).

**Table 2** Brain regions, cluster size, and associated cluster peaks for each contrast

Contrast	Hemisphere	Lobe	Approximate brain regions	Voxels	Volume (mm <sup>3</sup> )	Talairach coordinates (LPI) of peak activation			Statistics at peak voxel in cluster			
						x (LR)	y (PA)	z (IS)	$\beta$	<i>t</i>	<i>p</i>	<i>d<sub>z</sub></i>
Draw – New	Left and Right	Frontal	Medial Frontal Gyrus, BA 10	18	374	0	54	7	.12	4.15	.00054	0.93
List – New	Right	Cerebellum	Pyramis, Inferior Semi-Lunar Lobule	14	291	41	-70	-34	.14	4.19	.00050	0.94
	Right	Parietal	Cingulate Gyrus, BA 31	14	291	19	-42	35	.07	4.00	.00077	0.89
Write – New	-	-	-	-	-	-	-	-	-	-	-	-
Draw – Write	Left and Right	Frontal	Medial Frontal Gyrus, BA 10	91	1,893	3	54	-4	.28	4.41	.00030	0.99
	Left	Temporal/Parietal	Middle Temporal Gyrus, BA 39	59	1,227	-50	-64	26	.19	4.87	.00011	1.09
Draw – List	-	-	-	-	-	-	-	-	-	-	-	-
List – Write	Left	Temporal/Parietal	Middle Temporal Gyrus, BA 39	58	1,206	-50	-64	24	.18	3.95	.00086	0.88

Only statistically significant clusters are reported here: This was determined using cluster-size thresholding at the  $p < .001$  level while controlling false-discovery rate to the  $p < .05$  level. The  $p$ -value presented here is for the effect at the peak voxel of each cluster and is uncorrected. Brain regions listed here were within 2 mm of the peak voxel in each significant cluster. See our page on the Open Science Framework (OSF) for reports with % overlap values of each cluster across nearby brain regions. BA = Brodmann area, LPI = neurological coordinate order, LR = left-right dimension, PA = posterior-anterior dimension, IS = inferior-superior dimension

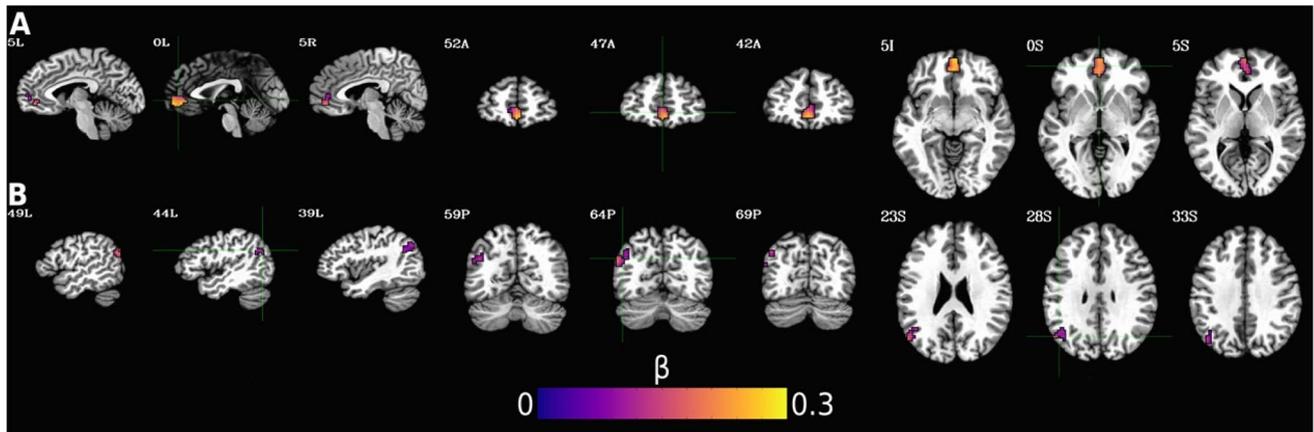
right superior frontal and left middle frontal gyri together present as bilateral clusters peaking in Brodmann area (BA) 6, revealing widespread brain-behaviour correlations in both the premotor and the supplementary motor areas (see Fig. 3). No negative brain-behaviour correlation clusters survived thresholding in this contrast.

For the sake of completeness, it is worth mentioning that the other two contrasts revealed only negative brain-behaviour correlations, which we do not interpret further: A single negative correlation cluster in the Draw – List contrast (35 voxels centered on  $x = -41$ ,  $y = -51$ ,  $z = -7$ ), and two negative correlation clusters in the List – Write contrast (32 voxels peaking at  $x = -25$ ,  $y = -51$ ,  $z = -18$ , and 20 voxels peaking at  $x = 28$ ,  $y = -21$ ,  $z = 57$ ; see files on OSF for more details).

## Discussion

Drawing as an encoding strategy has been shown to enhance memory in younger adults (Wammes et al., 2016, 2017, 2019, Wammes, Meade et al., 2018a, Wammes, Roberts et al., 2018b), as well as cognitively healthy older adults (Meade et al., 2020; Tran et al., 2022). Here, we investigated the neural regions underlying the drawing-induced memory benefit. We asked participants to either draw, write, or list physical characteristics of target words during encoding, and later scanned participants' brains while they performed a recognition memory test for the studied words. Behaviourally, memory was significantly higher for words drawn than written, replicating the typical drawing effect. Indeed, this pattern was present in 19 of 20 participants (with the remaining participant showing equivalent memory in the two conditions; see Fig. 1). Memory for words encoded by listing physical characteristics was also higher than for those written, but lower than those drawn. Voxel-wise analyses of fMRI data revealed a distributed set of brain regions active during recognition of words drawn relative to written at encoding, highlighting integration (angular gyrus) and self-referential processing (anterior prefrontal cortex). Brain-behaviour correlational analyses showed that memory for words drawn at encoding increased with activation in premotor and supplemental motor areas, as well as area V1 and the cuneus.

Wammes and colleagues (Wammes et al., 2016) have proposed that the drawing effect arises from engagement of motoric, elaborative semantic, and pictorial coding, all integrated seamlessly when one draws a to-be-remembered word during encoding (see also Fernandes et al., 2018, for a review, and Wammes et al., 2019). Moreover, it has been demonstrated previously that the act of drawing evokes neural activity in occipital (V1, V2, and lateral occipital cortex),



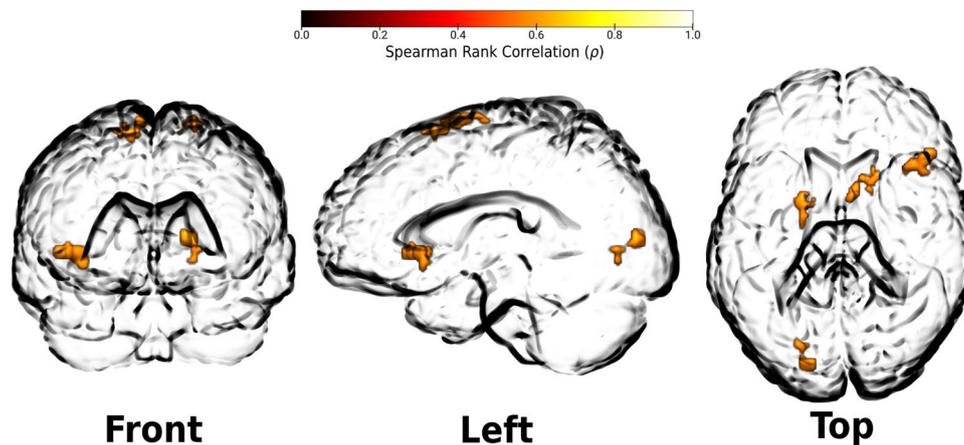
**Fig. 2** Neural activity differences in the contrast of draw – write. Functional images for the Draw – Write contrast are overlaid on a template brain. Sagittal scans are presented on the left, coronal scans in the middle, and axial scans on the right. XYZ coordinate labels are presented in LR-PA-IS format (L = left, R = right, P = posterior, A =

anterior, I = inferior, S = superior). The middle image for each scan view in a given panel contains crosshairs targeting the center of mass for the cluster, with images to the left and right extending out 5 mm. Panel A = BA 10, Panel B = BA 39

**Table 3** Brain areas wherein functional signal change correlated positively with memory performance for draw vs. write

Hemisphere	Lobe	Approximate brain regions	Voxels	Volume (mm <sup>3</sup> )	Talairach coordinates (LPI) of peak activation			Brain-behaviour correlation at peak voxel in cluster		
					x (LR)	y (PA)	z (IS)	$\rho$ (rho)	t	p
Right	Frontal	Inferior Frontal Gyrus, BA 47	37	769	41	24	2	.80	5.70	.00001
Right	Frontal	Superior Frontal Gyrus, BA 6	27	562	11	13	60	.75	4.83	.00006
Left	Occipital	Cuneus, BA 17	22	458	-17	-81	7	.77	5.09	.00003
Left	Frontal	Middle Frontal Gyrus, BA 6	20	416	-19	2	62	.74	4.61	.00010

Only statistically significant clusters are reported here; this was determined using cluster-size thresholding at the  $p < .01$  with a size threshold of 20 voxels. The  $p$ -value presented here is for the brain-behaviour correlation at the peak voxel of each cluster and is uncorrected. Brain regions listed here were within 3mm of the peak voxel in each significant cluster. BA = Brodmann area, LPI = neurological coordinate order, LR = left-right dimension, PA = posterior-anterior dimension, IS = inferior-superior dimension



**Fig. 3** Brain-behaviour correlations in the critical Draw – Write contrast. Significant clusters are shown, with positive brain-behaviour correlations ranging from 0 to 1, overlaid on a template brain using MRICroGL software (v. 1.2.20220720; Rorden & Brett, 2000)

parietal areas, and motor regions (Fan et al., 2020; Vinci-Booher et al., 2019). Given this, the neural basis of the drawing effect likely stems from the creation of visuospatial and motor representations of to-be-remembered information that supplement a semantic one, as well as perhaps integration of these various modes of representing target words.

## Interpretation of fMRI results

### Multimodal integration

When comparing memory for words that were drawn relative to written during encoding, significant activation was found in the left angular gyrus (AG; BA 39). This selective activation of the angular gyrus is somewhat unsurprising as it is a known hub for multimodal integration. Given that the AG sits at the junction of areas associated with sensory input, motor plans, comprehension, and emotion, researchers have suggested that it is particularly well situated anatomically to enable mental integration (Binder & Desai, 2011). In fact, meta-analyses (Binder et al., 2009; Kim, 2010), qualitative reviews (Binder et al., 2009; Humphreys et al., 2021), and primary research articles (Bonnici et al., 2016; Shannon & Buckner, 2004; Wagner et al., 2005; Yazar et al., 2014, 2017) have all highlighted the AG as a major centre for multimodal integration during episodic retrieval, leading some researchers to propose a ‘contextual integration model’ for the AG in the human cortex (Ramanan et al., 2018). That activity in this well-known hub for integration was greater during retrieval of words drawn relative to written at encoding suggests that the act of remembering a drawn word involves some degree of integration of multimodal representations.

Going beyond the draw versus write comparison, we also saw that listing physical characteristics of a word during encoding led to greater subsequent activation in the AG during recognition, compared to words that were written. The semantic characteristics that participants generated during the ‘list’ encoding task were often concrete visual attributes of the item. Thus, deep elaboration (listing semantic characteristics) may also engage the AG as it has been shown to play a role in integrating different pieces of semantic knowledge relating to an item (Kim et al., 2011; Noonan et al., 2013).

While we did not identify any significant clusters in the Draw-List contrast, there was a significant difference in behavioural memory performance. This disparity suggests that Draw and List words are represented similarly in the brain during recognition, but that there may be something extra driving performance for Draw items that we were unable to detect in our neuroimaging analyses, perhaps due to insufficient statistical power to detect what is likely a small effect. Indeed, when the statistical threshold for this contrast was lowered to  $p < .01$ , significant positive clusters emerged

around bilateral primary motor and somatosensory areas. We refrain from making conclusions based on these results due to the lower threshold used for detection, but these analyses seem to point to statistical power as the main reason for not detecting significant clusters at  $p < .001$  in this particular contrast.

### Goal maintenance and self-referential processing

By far, the largest cluster of activation observed in the critical draw versus write contrast was activation of the right anterior medial prefrontal cortex (aPFC). This region has been previously linked to self-referential processing (D’Argembeau et al., 2007; Kelley et al., 2002; Meyer & Lieberman, 2018; Nejad et al., 2013; van der Meer et al., 2010), and the ability to maintain multiple parallel goals (Charron & Koechlin, 2010; Euston et al., 2012; Koechlin et al., 1999). The medial aPFC has also been implicated when one attends to one’s own emotions and mental states (Gilbert et al., 2006). Given this, it may be that drawing facilitates subsequent memory because it enables greater self-referential processing during retrieval, ultimately aiding the retrieval process.

This same brain area is also known to act as an early unconscious decision-maker (Elliott et al., 1999) that collects information, makes a decision, and sends that decision to the SMA (Soon et al., 2008), which in turn outputs the decision as a motor response (i.e., a button press). Thus, the vast bilateral activation seen in the aPFC could be indicative of simultaneous goal pursuits to form mental imagery of one’s own drawing during the recognition test, culminating in a final response decision that gets forwarded to motor areas to be carried out via button-press.

### Brain-behaviour correlations

Positive brain-behaviour correlations were only found in the draw versus write comparison. Within this contrast, four significant clusters were observed. We found that activity in bilateral supplementary motor areas (SMAs) correlated positively with the size of the drawing effect. Beginning with Penfield’s early psychosurgery explorations of the human motor cortex in the 1950s, the SMA has been recognized for its role in internal generation of movement plans (Penfield & Welch, 1951). Subsequently, considerable evidence has implicated the SMA in complex motor sequences and responses on visuomotor tasks both in humans (e.g., Gerloff et al., 1997; Jenkins et al., 1994; Lee & Quessy, 2003; Roland et al., 1980; Shibasaki et al., 1993) and in macaque monkeys (e.g., Mushi-ake et al., 1990). If the function of the SMA is to form complex movements, why would it be preferentially activated during a recognition test that requires only a simple button press? One explanation can be found in related work that considered

the SMA (and other motor cortices) as key regions mediating retrieval of actions in monkeys (Passingham, 1989; Shima & Tanji, 1998) and humans (Gaymard et al., 1990, 1993). Neuroimaging work has similarly confirmed that the SMA is instrumental in not just motor planning for real actions, but for imagined actions as well (Cunnington et al., 1996; Dechent et al., 2004; Mehler et al., 2019; Ueno, 2003). Hence the bilateral SMA activation seen here could indicate that participants were re-imagining the motor sequences they used to form their previously created drawings. Indeed, a related literature on memory for enacted words has come to similar conclusions, supporting the notion that motoric re-activation during recall of previously performed actions can enhance memory (Roberts et al., 2022).

A number of voxels clustering in the inferior frontal gyrus (BA 47) were also correlated with memory performance for words drawn at encoding and may hint at a more nuanced story. Prior work suggests that BA 47 may be implicated in processing of stimuli unfolding over time (Levitin & Menon, 2003; Vuust et al., 2006), spatial working memory (Jonides et al., 1993), and episodic memory retrieval (Cabeza et al., 2002). If the SMA activity highlighted earlier is truly due to motor imagery at retrieval, then perhaps activity in BA 47 is evidence of a spatiotemporal dynamic in working memory whereby the sequence of hand movements used to draw the word is reinstated as part of the motor imagery experience.

Importantly, brain-behaviour correlational analyses also demonstrated evidence suggesting that recognition of words drawn relative to written at encoding invoked brain regions involved in visual imagery (left cuneus, also known as area V1, primary visual cortex, and BA 17). A plethora of studies have concluded that area V1 is involved in mental imagery in the absence of a visual stimulus (Chen et al., 1998; Klein et al., 2000; for a review, see Pearson et al., 2015). Indeed, activation of area V1 is reportedly similar when viewing a stimulus and imagining it (Reddy et al., 2010), and even maintains a retinotopic map for imagined content (Klein et al., 2004). That memory for drawn items increased as activity in this region increased suggests participants were re-imagining the drawing they made, or that the image of that drawing came to mind when making a recognition memory decision to the word it represents. It seems plausible, therefore, that participants were actively trying to recall their drawings by imagining them during the recognition test, in order to determine whether an item was previously studied. In fact, the angular gyrus (AG) – which had shown preferential activation during recognition of drawn items in our voxel-wise analyses – has also been shown to play a role in semantic matching of visual stimuli (Seghier et al., 2010), furthering the notion that correctly recognizing previously drawn items may be due to participants attempting to re-imagine their previously created drawings.

Overall, brain-behaviour correlations revealed that the size of one's memory benefit for words drawn relative to

written at encoding was positively correlated with activation in brain regions linked to motor imagery, mental visualization, and spatiotemporal ordering. While speculative, it seems plausible that this group of brain areas is indicative of a multidimensional cognitive effort to re-experience a drawing at retrieval. If a drawing can be re-instated in some capacity, we reason that a participant is more likely to correctly endorse the item as a previously studied word.

### Drawing as a multimodal heuristic

Because drawing at encoding is thought to be a multimodal activity, there are many ways in which target words could be later remembered. One can rely on recalling the generative process used to form a drawing, the mental image of a drawing they made, the motor sequences used to create it, or as we suggest here, all three simultaneously. Therefore, insofar as drawing evokes multimodal encoding during the study phase, that same memory can be more easily retrieved on the recognition test. This could be why drawn words are better remembered relative to those in the list condition, and why listing semantic characteristics in turn leads to better memory than writing the word over and over. When writing a target word repeatedly, however, a less diverse mental representation is formed. As such, participants have less prior information upon which to base their later memory decision. Having such little information to rely on during the recognition test, participants may be more likely to incorrectly classify previously written words as 'new'.

When listing semantic attributes in the 'list' condition, one may not have access to a motor sequence used to draw the item, but one still arguably maintains benefits from mental generation and, perhaps to a lesser extent, visual imagery. When listing physical characteristics of a noun, one likely pictures the item in their mind's eye before listing visual attributes of the item. For example, when given the word 'dog', one first imagines an image of a dog and then writes down 'tail', 'paws', 'four legs', 'furry', etc. As suggested previously, this could be why we see AG activation in the list condition: Mental imagery could be integrated with semantic knowledge in order to generate this list of attributes. The list can then be re-generated at retrieval, facilitating endorsement of the target word as previously studied.

While our explanation of the drawing benefit manifesting at retrieval is speculative, it seems to align with the notion of re-living a drawing. Taking advantage of the multimodal nature of a drawn item in memory and re-experiencing it are potent ways to determine whether an item has been previously studied or not. That brain areas preferentially activated for correctly endorsed drawn words involved aspects of movement, mental imagery, and semantic integration supports this notion. Furthermore, that activation of brain regions reasonably associated with re-living a drawing

(SMA, V1, etc.) correlated positively with the *size* of the drawing benefit suggests that using the simple heuristic of ‘Did I draw that?’ allows one to take advantage of the rich multimodal representations formed at encoding (or, lack thereof) in order to make a memory decision.

## Limitations and future directions

This study was the first to investigate the neural basis of the drawing benefit on memory. As such, it has its limitations. First, our experimental paradigm consisted of 30 words per condition. Because fewer correct responses were made for targets from the Write relative to the Draw and List conditions, there were fewer trials available to contribute to the neural analysis. Ultimately this means the fMRI signal for the Write condition was less reliable. Future fMRI work could address this limitation by removing one of the comparator conditions (write or list) in the experiment, allowing more hits to occur for the two remaining conditions.

It is also worth noting that while in this study we have inferred the presence of specific cognitive processes from observed brain activation patterns, these are reverse inferences being made in an exploratory context. We are not suggesting that a given brain region performs a cognitive function exclusively, rather we base our discussion and conclusions on findings and suggestions from multiple other published studies that implicate a particular brain region in a given cognitive function. Here we aimed to document the network of regions that are present during retrieval of drawn relative to written or listed words. Overall, our results suggest drawing benefits memory by coactivating multiple sensory traces. Target words drawn during encoding are subsequently remembered by re-engaging visual, motoric, and semantic representations.

Our work suggests that encoding strategies that encourage creation and integration of multiple representations during encoding create a more robust memory trace. However, we did not assess whether variations in ability to *integrate* such representations limits the drawing benefit to memory. We are currently conducting a study in children to consider whether limited frontal-lobe-mediated executive functioning, required for ‘integration’, limits the benefit of drawing on memory. Those data would arguably be better suited to supporting an integration account of drawing’s benefit. A corollary to this would be that targets that are drawn at encoding should be better able to withstand the negative effects of multi-tasking. That is, if one representation is blocked there, memory can be sustained by the other representations. An obvious future experiment, therefore, is to compare retrieval of words drawn versus written at encoding when items are encoded or retrieved under divided-attention conditions.

Finally, while we had a priori predictions, we did not pre-register our predictions, and we chose to conduct a voxel-wise analysis rather than a region of interest (ROI) analysis, or pattern-based investigations like multi-voxel pattern analysis (MVPA) or representational similarity analysis (RSA). We made this decision because we felt that the first foray into brain regions supporting retrieval of words drawn at encoding should be exploratory. Subsequent work can specifically target ROIs found here to refine our conclusions. An ideal follow-up study would allow for multi-voxel pattern analysis to directly address the claims put forward here that there is a distributed network activated during retrieval of drawn words, involved in integration and self-referential processing (angular gyrus, anterior prefrontal cortex), and another implicated in mental/visual imagery (cuneus).

## Conclusions

The goal of this study was to explore neural mechanisms driving the large and reliable memory improvements following drawing as an encoding strategy. Behavioural data demonstrated a clear and reliable benefit of drawing over and above both listing and writing as encoding techniques. Listing semantic characteristics of words also improved memory relative to writing. Voxel-wise analyses of fMRI data revealed significant activation clusters in two distinct brain regions that were preferentially activated when remembering drawn relative to written words. These clusters peaked in right medial frontal cortex and left angular gyrus. Further brain-behaviour correlations suggested that the magnitude of the drawing effect on memory correlated positively with activity in bilateral supplementary motor areas, right prefrontal cortex, and left primary visual cortex. Overall, we found that retrieval of words drawn at encoding invoked activation of brain regions involved in integration, self-referential processing, and mental/visual imagery. We suggest that during recognition of drawn words participants are likely using a simple heuristic – ‘Did I draw that?’ – to elicit multimodal memory retrieval in an effort to weigh evidence for a recognition memory decision.

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**Availability of data, code, and materials** All data, analysis code, experiment programs, and other materials are listed on the Open Science Framework (OSF; <https://osf.io/74mdc/>).

## Declarations

**Competing interests** Not applicable.

**Ethics approval** The procedures and materials for this study were approved by the Office of Research Ethics at the University of Waterloo and the Tri-Hospital Research Ethics Board at Grand River Hospital.

**Consent to participate** Informed consent was obtained from all individual participants included in the study.

**Consent for publication** Not applicable.

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