

Temporal decoding of selective recollection with psychophysiology

Bial Foundation Grant # 169/18

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Overview

- a) A first paper from the project has been accepted for publication in Cognitive, Affective and Behavioral Neuroscience, reporting event-related potentials from Experiment Two's electroencephalographic (EEG) data. The accepted manuscript is attached.
- b) The second paper is in draft and is attached. This reports the main multivariate decoding analysis of Experiment Two's (EEG) data along with another complete decoding experiment. Submission is expected in February 2021.
- c) EEG data collection from Experiment One are complete and analysis is in progress (this experiment was subject to substantial delay during the pandemic). Initial findings from the supplementary behavioural Experiment One-B are reported below. These data are expected to contribute to 1 or 2 further scientific papers.

Aims

1. To increase knowledge about psychophysiological processes supporting recollection.
2. To use multivariate decoding ERP methods to measure how recollected representations emerge during recall
3. To investigate whether these recollected representations are selective (dependent on current goals).

Note: Experiments are reported in the order in which they were conducted, changed as a result of the pandemic. The original numberings from the funding proposal have been retained, with additional indices referring to the publications (Experiment Two-1 and Experiment Two-2 correspond to Experiments 1 and 2 in Moccia and Morcom, in press, and Moccia et al., in prep).

EEG Experiment Two

Experiment Two addressed all three aims of the project. Because the originally planned study was amended and combined with an additional experiment, yielding striking findings regarding external memory cues, the univariate data were published separately (Moccia and Morcom, in press). The multivariate decoding data for both studies will be published in the second paper, Moccia et al. (in prep). Further details of background, methodology and results can be found in these (attached).

Methods

Participants

Twenty-eight participants were tested, and none excluded (20 female, M = 22.79 years, SD = 4.14). A further 29 were tested in a second experiment, of which 28 were included (20 female, M = 24.57 years, SD = 3.71), and one excluded due to too few artefact-free trials.

Instruments and Measures

Stimuli. Stimuli were pictures and names of 240 common objects. In the study phase, stimuli were either coloured pictures or auditory words spoken by a native English male voice. In the test phase, retrieval cues were visual words (Experiment Two-1) or grey-scale line drawings (Experiment Two-2). For each of two study-test cycles, 40 pictures and 40 auditory words were combined to create a study list of 80 items. The corresponding visual words or line drawings were then combined with 40 new (unstudied) items to create the test list of 120 items. For each study-test cycle, half the items were allocated to each of two test blocks. Two further unstudied filler pictures were added at the start of each study list, and two at the start of each test block, and 12 items served in practice lists. Item order was determined randomly within each study and test list.

Behavioural procedure. The EEG was recorded in two experiments using a recognition memory exclusion task in which retrieval goals are manipulated ¹. The task involved two study-test cycles.

At study, participants saw pictures or heard auditory words and were asked to learn the items for a later memory test, and rate their pleasantness on a 4-point scale. On each trial, a preparatory cue (pre-cue) presented for 1,000 ms signaled the format of the coming item with either a yellow asterisk or a blue lowercase o (allocation of symbols to conditions was counterbalanced). The screen was then blanked for 100 ms before the stimulus was presented for 1,000 ms, followed by a 1,500 ms red fixation cross. The word "RESPOND" then appeared centrally on screen for up to 3,000 ms while participants responded using keypresses, followed by a 100 ms blank screen.

At test, after a brief unrelated distractor task, participants completed 2 memory test blocks with different retrieval goals. In each block, studied objects presented in one format were designated as targets (Target-Audio or Target-Pictures). For example, in the Target-Audio block, participants were instructed to respond 'yes' to items that they remembered hearing as object names in the preceding study phase and 'no' to all other items. The same preparatory symbols as at study also reminded participants of this target designation for 500 ms, before a black fixation '+' for 1,800 ms. The retrieval cues (visual words or line drawings) were then shown centrally on the screen for 3,000 ms followed by a red fixation for 500 ms in Experiment Two-1, and 500 ms followed by a 3,000 ms fixation in Experiment Two-2. Responses were recorded during stimulus presentation in Experiment Two-1 and during fixation in Experiment Two-2.

EEG recording and preprocessing. EEG data were recorded with a BioSemi Active Two AD-box with 24-bit signal digitization from 64 active silver/silver chloride electrodes in an elastic cap using the extended International 10-20 system configuration. Vertical and horizontal eye movements (electrooculogram; EOG) were recorded with bipolar electrodes above and below the right eye and on the outer canthi. EEG and EOG signals were acquired continuously at 1024-Hz with amplifier bandwidth of 0 ± 208 Hz (3 dB), referenced to a CMS electrode. EEG data were preprocessed using EEGLAB and MATLAB R2018a. A 0.1-40 Hz Hamming windowed-sinc FIR and a 50 Hz notch filter for line noise were applied after re-referencing the raw signal to linked mastoid electrodes. Following automatic rejection of gross artefacts, the data were partitioned into epochs including pre-cue and stimulus, time-locked to the stimulus onset (4,500 ms epochs for study and 6,700 ms for test). Vertical and horizontal EOG artefacts were corrected using Independent Component Analysis (ICA) with manual removal of components.

For the multivariate decoding analysis, we also smoothed the ERP data using a 20 ms full-width half-maximum Gaussian kernel to increase signal-to-noise.

EEG analysis. The behavioural and univariate ERP analyses were preregistered. Statistical analyses were conducted in R 3.6.1 for univariate data and R 3.5.4 for multivariate data (<https://www.r-project.org>) and JASP (version 0.15.0.0, <https://jasp-stats.org/>). Alpha was set at .05. In analyses of variance (ANOVAs) we applied a Greenhouse-Geisser non-sphericity correction where appropriate. Electrophysiological analysis examined effects of target designation and item type for targets (items studied as pictures in the Target-Pictures condition or as auditory words in the Target-Audio condition), and for non-targets and new items. Mean number of trials (range) contributing to ERPs in Experiment Two-1 for target hits, non-target CRs, and new CRs were 31 (14-37), 33 (18-39), and 35 (21-40) in the Target-Pictures block, and 29 (18-38), 34 (25-40), 33 (21-40) in the Target-Audio block. In Experiment Two-2, there were 33 (25-38), 32 (22-36), and 35 (25-40) in the Target-Pictures block, and 25 (15-34), 34 (30-38), 29 (16-38) in the Target-Audio block.

Univariate analysis quantified the mean per-participant ERP amplitudes for correct responses in each experimental condition (target hits, non-target correct rejections [CRs], and new CRs) according to target designation (Target-Pictures and Target-Audio). ERPs time-locked to both pre-cues and retrieval cues were analysed.

To identify neural reinstatement, multivariate decoding of ERP data employed linear discriminant analysis (LDA) with shrinkage regularization implemented in custom-written MATLAB code (version 2019b) and functions adapted from Linde-Domingo et al. (2019). LDA classification was performed separately for each participant.

Results and Discussion

For fuller explorations of the univariate results see Moccia and Morcom (in press; attached); for complete multivariate findings, see Moccia et al. (in prep; attached).

Univariate ERPs

To examine the selectivity of target over non-target recollection, we examined the left parietal ERP in an *a priori* analysis of data from 3 parietal electrodes (P1/P3/P5) from 500-800 ms post-stimulus. The waveforms are illustrated in Figure 1 (reprinted in part from Moccia & Morcom, in press).

Selectivity was quantified as difference waves for targets minus non-targets and subjected to ANOVA with the within-participants factor of Target Designation (picture/audio) and the between-groups factor of Experiment (Two-1/ Two-2). This revealed a significant interaction of Cue Type and Target Designation $F(1, 54) = 38.04, p < .001, \eta^2_p = .413$. *Post hoc t*-tests confirmed that target and non-target left parietal effects differed more in the Target-Audio condition when cues were words (Experiment 1) as opposed to line drawings (Experiment 2), $t(54) = 4.39, p < .001, d = 1.17$, while selection in the Target-Picture condition was stronger when cues were line drawings, $t(54) = -5.01, p < .001, d = 1.34$.

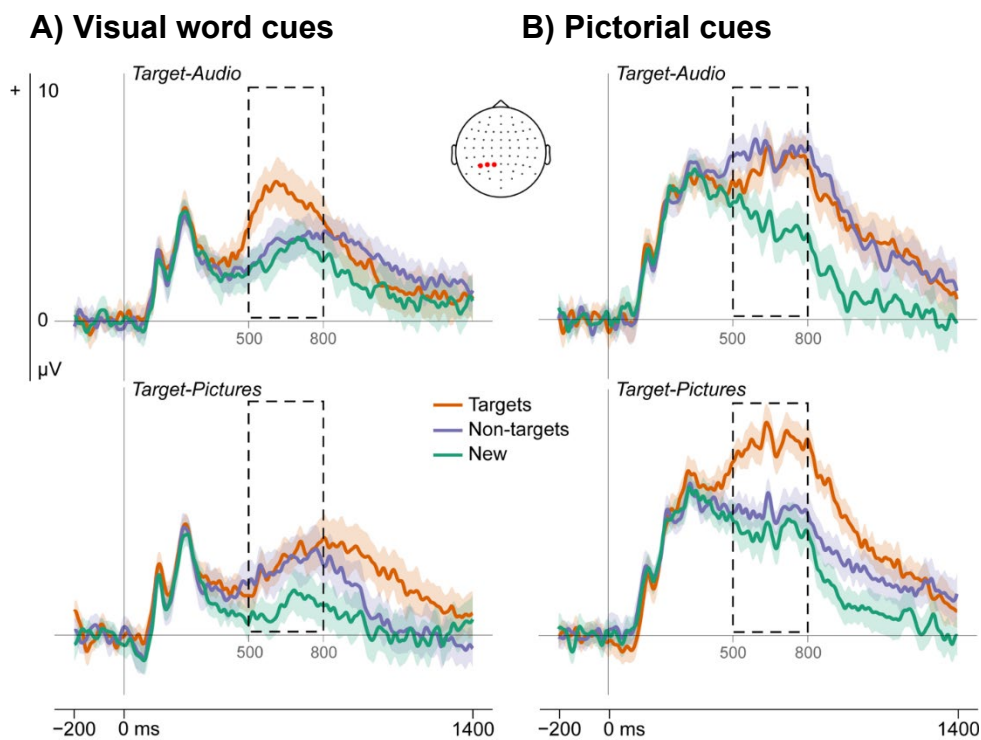


Figure 1. Effects of target designation and retrieval cues on selectivity of left parietal ERP effects. Panels A) Experiment Two-1) and B) Experiment Two-2) show mean grand-average ERP waveforms for target hits, non-target CRs, and new CRs over electrode sites (P1, P3, P5; see inset), plotted separately by Target Designation for each Experiment. The dashed areas indicate the analysed time-window of 500-800 ms. The shaded areas represent the 95% confidence intervals for each time-point.

Post hoc analysis showed that in Experiment Two-1, when retrieval cues were visual words, recollection as measured by the left parietal ERP was target-selective when targets were studied

auditory words – with high overlap with the retrieval cues – but was non-selective when targets were studied pictures. *Post hoc* t-tests for the Target-Audio block showed that left parietal ERPs for target hits were significantly more positive than for both non-target CRs, $t(27) = 4.19$, $p < .001$, $d = 0.52$ and new CRs, $t(27) = 4.57$, $p < .001$, $d = 0.65$, and the latter were statistically indistinguishable, $t(27) = 0.95$, $p = .420$, $d = 0.13$. In contrast, in the Target-Pictures block – when cue-target overlap was low – left parietal ERPs evoked by both targets and non-targets were significantly more positive than those for new items, $t(27) = 4.77$, $p < .001$, $d = 0.64$, and $t(27) = 3.36$, $p = .004$, $d = 0.51$, while target and non-target ERPs did not differ significantly, $t(27) = 0.29$, $p = .775$, $d = 0.04$.

We observed a complementary pattern of ERP selectivity in Experiment Two-2, when retrieval cues were pictorial: target recollection was non-selective when auditory words were targets but selective when pictures were targets, i.e., when overlap between retrieval cues and targets was high. *Post hoc* t-tests showed that in the Target-Audio block ERPs to both target hits and non-target CRs were significantly more positive than new CRs, $t(27) = 5.16$, $p < .001$, $d = 0.57$, and $t(27) = 5.60$, $p < .001$, $d = 0.67$. Target ERPs were non-significantly more negative-going than non-target ERPs, $t(27) = -1.74$, $p = .094$, $d = 0.13$. In contrast, target prioritization was significant, and more pronounced, in the Target-Pictures block. Here, ERPs evoked by target hits were significantly larger than those for non-target CRs, $t(27) = 9.22$, $p < .001$, $d = 0.64$, although both were significantly more positive than new CRs, $t(27) = 9.25$, $p < .001$, $d = 0.84$ for targets versus new, and $t(27) = 2.55$, $p = .018$, $d = 0.21$ for non-targets versus new.

This asymmetric pattern of selectivity could not be explained by easier recollection of targets, as has been proposed². Regardless of target designation, responses were slightly more accurate and faster to items studied as pictures. But we found target-selective left parietal ERPs only for the high-overlap conditions. In Experiment Two-1 retrieval cues were visual words, overlapping more strongly with targets studied as audios than as pictures, and in Experiment Two-2 the cues were picture line drawings with greater overlap with the picture than the audio source. The data thus favour a cue-overlap account, suggesting that pre-retrieval selection was effective only when people target a memory course that has high overlap with external retrieval cues.

These ERP asymmetries go beyond findings of previous studies showing selectivity of the left parietal effect when targets were identical to the cues shown at test^{2,3}. We show for the first time that cue-target overlap has downstream consequences for successful retrieval even when overlap is incomplete, i.e., participants' memory is probed with retrieval cues that were not identical 'copy cues' of studied items, and when both verbal and pictorial cues are used (see also Czernochowski et al., 2005). Together, the data support the view that cue-target overlap is a critical factor enabling selection prior to recollection. These findings extend support for the longstanding principle of encoding specificity, which assumes that cues trigger recollection when they elicit representations that overlap with stored memory traces (Morris et al., 1977; Tulving & Thomson, 1973).

Multivariate decoding

To identify neural reinstatement, we used multivariate decoding analysis to assess the similarity between EEG neural patterns at study and at test. Our analysis focused on neural patterns that related to distinct types of remembered episodes, i.e., differed between hearing auditory words and seeing pictures at study. Multivariate noise normalization was applied on a single trial basis^{7,8}. Trials were subsampled to ensure equal numbers per class and the outcomes averaged over 12 iterations. We measured reinstatement by training LDA classifiers on study phase data to discriminate between pictures and auditory words, then testing them on (independent) test phase ERPs. For analysis of retrieval cue epochs data were downsampled to approx. 8 ms time bins prior to decoding and test phase ERPs were baseline-corrected. For analysis of pre-cue epochs, data were downsampled to approx. 15 ms time bins.

Retrieval cue epochs. First, we decoded information about study format from neural patterns during successful recollection using ERPs elicited by the retrieval cues on trials attracting correct responses. Cross-classification of study and test data paired each training time point (study phase, from 136-1000 ms) with each test time point (test phase), yielding a matrix of values. The test phase time window of interest for the analyses reported here was 200-800 ms. For statistical analysis, the strength of reinstatement was quantified using the classifier fidelity measure d which indicated the distance to the decision boundary that divided the two classes (study formats) in the classifier's high-dimensional space. Mean d values were computed for study phase neural patterns from 4 *a priori* time windows. The S1 (136-232 ms) and S2 (240-360 ms) windows followed⁸, and the second two were derived from a study phase decoding analysis of Experiment Two-1, S3 (368-672 ms) and S4 (680-984 ms). The test phase data were divided into an early and late time window (203-487 ms and 495-776 ms): the late window is the same as used to measure the left parietal ERP (above).

We assessed neural reinstatement for targets and non-targets according to target designation (Target-Picture and Target-Audio) by testing the trained LDA classifiers on the target or non-target test phase data versus the new items, for which no information should be retrieved. These new items were always those from the same test block, to control for effects due to differing retrieval goals. Initial exploratory decoding (see Moccia et al., in prep, attached) revealed significant neural reinstatement of studied information during test in approximately the same time window post-stimulus as the left parietal ERP. Importantly, non-target as well as target reinstatement was prominent in the two conditions which had shown a non-selective pattern for the left parietal ERP.

Direct comparisons of the amount of target and non-target reinstatement were therefore needed, and this was achieved using outputs obtained by decoding reinstatement of information from the 4 *a priori* study phase time windows. We first established qualitative differences in the neural patterns reinstated when people remembered items studied as audios versus pictures, whether targets or non-targets. When people recalled items studied as audios they reinstated neural patterns from the early (S1) study time window, but when they recalled items studied as pictures they reinstated patterns from the later study windows (S3-S4). This was consistent with many fMRI studies showing that neural patterns at retrieval depend on recollection contents^{9,10}. We therefore quantified audio and picture reinstatement from the study windows in which each was maximal: S1 and S3, respectively. Figure 2 contrasts the pattern of reinstatement selectivity revealed by this multivariate decoding analysis (Fig 2B) with the pattern of univariate left parietal ERP selectivity previously reported by Moccia and Morcom (2021) (Fig 2A; for corresponding waveforms, see Fig 1).

In Experiment Two-1 (when cues were verbal), repeated measures ANOVA on mean classifier fidelity values with factors of target designation (target-picture/ target-audio), trial type (target/ non-target) and test window (early/ late) showed an interaction of target designation with test window, $F(1,27) = 5.40$, $p = .028$, $\eta^2_p = .167$. *Post hoc* analysis of differences between target and non-target reinstatement in each test window confirmed that reinstatement was selective in the late test window only, $F(1,27) = 5.73$, $p = .024$, $\eta^2_p = .175$, for early window, $F(1,27) = 0.002$, $p = .964$, $\eta^2_p < .001$. In Experiment Two-2 (when cues were pictorial) there was a similar but stronger pattern, with a 2-way interaction of trial type with test window, $F(1,27) = 17.73$, $p < .001$, $\eta^2_p = .396$. This again reflected strong selectivity in the late window, $F(1,27) = 26.54$, $p < .001$, $\eta^2_p = .496$, and no significant reinstatement in the early window, $F(1,27) = 1.69$, $p = .203$, $\eta^2_p = .059$. Main effects of trial type, $F(1,27) = 13.79$, $p < .001$, $\eta^2_p = .338$, test window, $F(1,27) = 9.51$, $p = .005$, $\eta^2_p = .261$ and target designation, $F(1,27) = 9.26$, $p = .005$, $\eta^2_p = .255$ were also significant. A direct comparison between experiments in the late test window also confirmed that reinstatement was highly target-selective: ANOVA with factors of target designation (target-picture/ target-audio), trial type (target/ non-target) and experiment (Two-1/ Two-2) yielded a significant main effect of trial type, $F(1,27) = 27.85$, $p < .001$, $\eta^2_p = .340$. Moreover, an equivalent Bayesian ANOVA showed strong evidence

against including the interaction of target designation with test block in the model, $BF_{01} = 6.24$, or the 3-way interaction of both these factors with experiment, $BF_{01} = 4.76$.

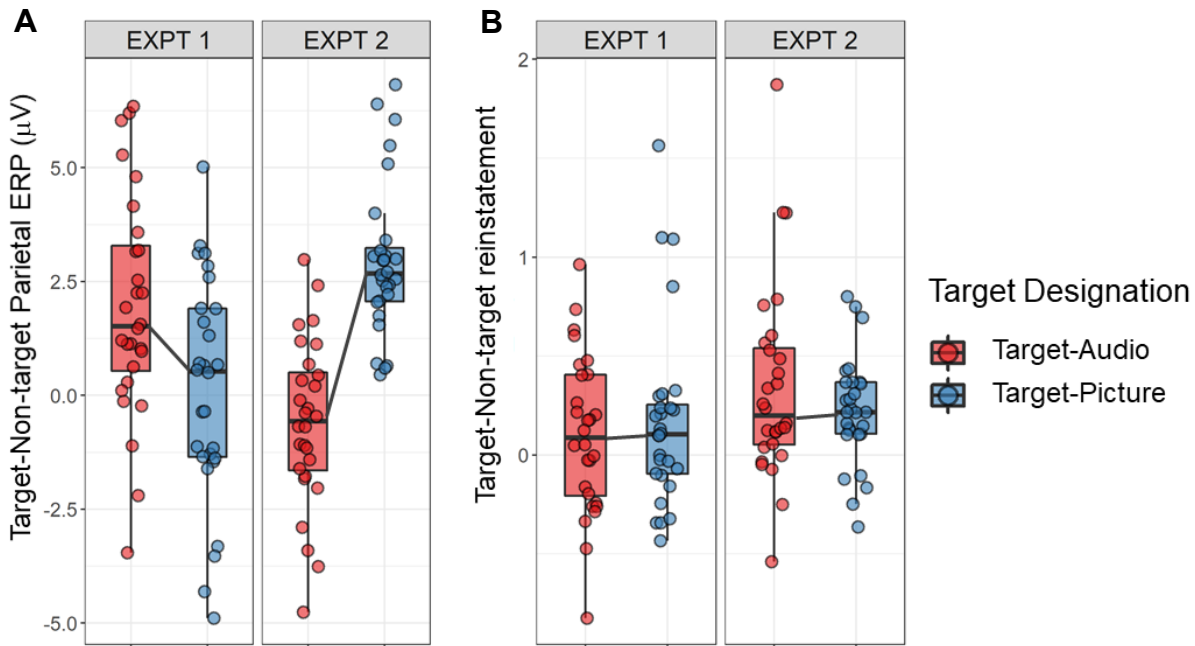


Figure 2. Comparison of target-selectivity at two stages of recollection. Data shown in both panels are difference measures for studied targets versus non-targets. Target designation refers to whether targets are items studied as audios or pictures. In Experiment Two-1, retrieval cues were visual words, and in Experiment Two-2 they were pictorial line drawings. A) Univariate ERP data from Moccia & Morcom (2021): the left parietal ERP was target-selective when retrieval cues had high overlap with targets, i.e., in the target-audio block in Experiment Two-1 and the target-picture block in Experiment Two-2. In the other blocks, the left parietal ERP was present for non-targets as well as targets (non-selective). B) Reinstatement selectivity computed with LDA in the present study: neural reinstatement is selective, but selectivity does not depend on the current target designation or the test cue; i.e., it is present across blocks and experiments.

Preparatory cue epochs. Lastly, we examined neural reinstatement associated with maintaining a retrieval goal before any specific retrieval cue was presented. To do this, we applied the LDA classifiers trained on the study phase to decode the neural patterns during the pre-cue interval at test. In Experiment 1, the LDA classifier trained to differentiate picture and audio trials at study was able to distinguish at test between preparation to retrieve picture targets and preparation to retrieve audio targets: the classifier fidelity measure revealed three significant clusters of reinstatement from approx. 400 - 1200 ms after the preparatory cue (cluster permutation test with initial p threshold = .05 and family-wise $\alpha = .05$, $p = .006$, $p = .006$), and a further cluster just before retrieval cue onset ($p = .023$). This showed sustained proactive reinstatement of the currently relevant study context while participants prepared to target items studied in one of the two formats. However, in Experiment 2, the classifier did not significantly decode the retrieval goal.

In the multivariate EEG decoding study we demonstrated selective reinstatement of goal-relevant neural patterns during recollection. Reinstated study phase neural patterns were stronger when people recalled items designated as targets, showing that goal-relevant recollection was prioritized, although selection was incomplete as some non-target information was also reinstated. Critically, neural reinstatement was consistently target-selective regardless of whether the targets had high or low overlap with the external retrieval cues – words in Experiment Two-1 and pictures in Experiment Two-2. As Fig 2 shows, this differed strikingly from the left parietal ERP, which had previously been shown to be target-selective only when cue overlap was high ¹¹.

Recollection is thought to occur when a cue partially reinstates neural patterns associated with a stored memory trace^{12–14}. This partial cue then triggers pattern completion by the hippocampus, leading to the reinstatement in cortex of distributed neural patterns that represented the original experience^{9,15,16}. Reinstated cortical representations have been hypothesized to support the vivid and multi-dimensional experience referred to as ‘reliving the past’^{9,10,17}. Alternatively, neural reinstatement may be necessary but not sufficient for recollection, as it can be just as strong when people fail to recollect as when they succeed^{18,19}. Initial reinstatement may be an automatic consequence of pattern completion²⁰ and subject to further, constructive processing^{8,16}. A simple model of the retrieval cascade assumes that selection may operate at two non-exclusive stages. If selection occurs at the early stage, target memories are selected prior to pattern completion so non-target memories are not reinstated. This predicts that reinstatement will follow the same pattern of selection as the left parietal ERP. If selection occurs at the late stage, both target and non-target information will be reinstated but later processing amplifies target information. This predicts that reinstatement will show a nonselective pattern while the left parietal ERP is selective for target memories.

These new results show that selection impacts recollection at both early and late stages of the retrieval cascade, and suggest that internal goals modulate the initial reinstatement of remembered information, while external cues modify its subsequent processing. Decoding of the preparatory cue data also revealed preliminary evidence – in one of two experiments – of the goal representations that have been hypothesized to initiate selective recollection via ‘mental reinstatement’^{21,22}. The results are also in line with previous EEG decoding studies that have suggested that neural patterns emerging very early in retrieval may interact with external cues to prioritize recollection in line with the encoding specificity principle²³ see also^{24,25} and^{26–28}.

EEG Experiment One

This experiment is addressing the effects of current goals on recollection by examining neural reinstatement that is incidental to the memory test. If recollection is holistic – i.e., if all the elements of the stored memory trace are reinstated together, as has been proposed²⁹ – then memory neural patterns will contain information about event elements that have not been tested (here, scenes) as well as those that have been tested (here, study format).

Methods

Participants.

Thirty-two participants were tested, of whom 28 provided sufficient data for the main analysis (17 female, 10 male, $M = 21.78$, $SD = 4.51$). A further 21 individuals participated in pilot testing.

Instruments and Measures

Stimuli. Stimuli were 15 images of indoor and outdoor scenes, and images and names of 216 objects. The scenes were a subset of those used by Konkle, Brady, Alvarez and Oliva (2012), and black-and-white line drawing object images from the same set as Experiment Two. The line drawing images were chosen following pilot testing conducted to balance a good level of memory performance with sufficient source miss trials for EEG analysis. As in Experiment Two, in the study phase half the objects were presented as images and half as spoken object names. Each studied object was also paired with one of the scenes. On each test trial, the retrieval cue was the visually presented name of one of the studied objects. Stimulus lists for each of 3 study phase blocks comprised 60 trials in which 2 scenes were each paired with 30 objects. The lists for each of the 3 corresponding test blocks comprised 72 trials, of which 30 had been studied as audios, 30 as pictures and 12 were new. Item allocation to conditions and cycles was randomized. A further 2 scenes and 8 objects were used to create practice lists.

Behavioural procedure. The EEG was recorded during a single study-test cycle in which participants performed a source memory task consisting of 3 short study blocks followed by 3 short test blocks.

At study, participants saw pictures or heard auditory words and were asked to learn the items for a later memory test, and rate both the 'fit' between the object and the scene, and their pleasantness, each on a 4-point scale. The two judgements were combined because pilot testing indicated they yielded a good level of both item and source memory. On each trial, the scene was first presented for 1,000 ms, followed by a fixation '+' sign for 100 ms before the stimulus was presented for 1,000 ms. Participants were then signaled for 1,000 ms to give their 'fit' rating, which was self-paced, then followed by a 500 ms fixation cross, then a signal to provide their 'pleasantness' rating. Finally, a 1,000 ms blank screen preceded the next trial.

At test, after a brief unrelated distractor task, participants viewed the names of studied objects and were asked to judge their memory for the object and for the format in which it had been studied. They were instructed to respond 'Seen' or 'Heard' if they were sure that they remembered a picture of the named object or its spoken name (respectively) from the study phase, 'Unsure' if they remembered the object but had no specific memory of how it was presented, and 'None' if they had no memory of the object being presented at study. Trials began with a fixation '+' for 500 ms, then the retrieval cue word was shown centrally on-screen for 3,000 ms followed by a signal to respond for a self-paced interval of at least 2,000 ms. Afterwards, a blank screen with jittered intervals randomly selected from 600, 700, 800, 900 or 1,000 ms preceded the next trial.

EEG recording and preprocessing. EEG and EOG data were recorded with NeuroScan SynAmps2 amplifiers and SCAN 4.3 software (NeuroScan/Compumedics, Inc.) at a 1,000 Hz. A physical band-pass filter was applied to online recording (0.10–100 Hz). Data were acquired from 64 scalp and 4 EOG electrode sites (see Experiment Two) as well as the mastoids, using Ag-AgCl electrodes. EOG electrodes were placed laterally to the canthi and above the left eye. Data were referenced to the left mastoid during recording then re-referenced offline to the average mastoid signal. EEG filtering and artefact rejection followed the same procedures as for Experiment Two, and are complete.

Results and Discussion

Behavioural analysis. Performance was analysed in terms of item memory and source memory. Studied items that were identified as studied (attracting Seen, Heard or Unsure judgements) were classified as hits, and new items that attracted the same responses were classified as false alarms (FA). Item memory was quantified as $Pr = p(\text{old hit}) - p(\text{new FA})$. Pr for audio items was .57 and for picture items it was .51. Studied items that were correctly identified as either 'Seen' or 'Heard' were classified as source hits, and those that were incorrectly identified or judged 'Unsure' were classified as source misses. Source memory accuracy was .68 overall, and .80 for confident responses.

EEG analysis (in progress). Twenty-eight participants have sufficient trials to decode scene reinstatement for source hits and 15 for a refined comparison of source hits versus misses.

Behavioural Experiment One-B

The goal of this study was to obtain a behavioural measure of holistic recollection by explicitly testing for statistical dependency between the retrieval of the two different event elements: scene context and study format, thus addressing a limitation of Experiment One.

Methods

Participants

Sixty-six participants were tested using the online platform www.Prolific.co (40 female, $M = 26.53$ years, $SD = 5.14$), of whom 60 provided sufficient data for analysis.

Instruments and Measures

The materials and procedure followed those of Experiment One, except participants studied images of scenes with images of famous faces, as well as with objects. Only differences are noted here.

Stimuli. Stimuli were 16 images of scenes, 16 images of famous faces, and coloured images and spoken names of 96 objects taken from Experiment Two. A single stimulus list for the study phase comprised 96 trials in which a studied object was combined with one of the scenes and one of the faces. A single test list comprised 96 trials, of which 24 had been studied as audios with outdoor scenes, 24 studied as audios with indoor scenes, 24 had been studied as pictures with outdoor scenes and 24 as pictures with indoor scenes. On half of the trials in each of the 4 conditions the visual object name test cue was paired with the face image previously studied with that object, creating cue and no-cue conditions.

Behavioural procedure. The memory task comprised a single study-test cycle. At study, participants saw faces and scenes combined with either pictures or auditory words and were asked to rate the 'fit' between the three event elements on a 4-point scale. Scenes, faces and objects were presented simultaneously. At test, after a brief unrelated distractor task, participants viewed the names of studied objects and were asked to judge their memory for the object and for the format in which it had been studied, as well as for the scene with which it had been studied. For the format decision, the keypress response options were the same as in Experiment One: participants judged whether they were sure that they remembered a 'Seen' picture of the named object or its 'Heard' spoken name from the study phase, or if they were 'Unsure' reflecting no available source memory, or 'None' if they forgotten that the object was presented at study. For the scene decision, the corresponding response options were 'Indoor' or 'Outdoor', referring to the category of the scene previously studied with the object, or 'Unsure' or 'None'. The order of the judgements was counterbalanced over participants. On half of the test trials participants were also shown the face that the object had been studied, with no specific instruction.

Results and Discussion

Source memory and cue effects.

Before analysing dependency between the two source memory outcomes, we assessed whether presence of the face cues improved performance, computing source accuracy for confident responses only ('Seen' and 'Heard', 'Outdoor' or 'Indoor'). Performance was higher for the scene than the format source, but cues had little effect: $M = .80$ and $.77$ for scene-cue and no-cue conditions, and $.70$ and $.69$ for format cue and no-cue conditions. ANOVA with factors of source type (format/ scene) and cue condition (cue/ no-cue) confirmed only a significant main effect of source type, $F(1,59) = 21.10$, $p < .001$ (for main effect of cue, $F(1,59) = 1.72$, $p = .194$ and for the interaction, $F(1,59) = .23$, $p = .627$). This does not support the prediction from the holistic recollection theory that cueing with one source element (here, a face) would increase recollection of other event elements (here, scene and study format). However, in previous experiments (in prep), we have shown effects of external scene cues on memory for study format, so our provisional hypothesis is that scene context is a more potent cue, as expected if spatial information has a special status in episodic memory³⁰.

Dependency in recollection of multiple source elements.

Following Horner and others, we next computed a measure of the trial-by-trial dependency between scene and format recollection. This D index is corrected for the overall level of performance³¹ by comparing the proportion of trials on which both source elements are correctly or incorrectly recalled together with the proportion expected on a null model in which recall of the two elements is independent. Dependency was significantly greater than zero for both the cue condition, $D = .037$, $t(59) = 3.02$, $p = .002$, and the no-cue condition, $D = .035$, $t(59) = 3.92$, $p < .001$, but the two did not

differ significantly, $t(59) = 0.109$, $p = .542$. Moreover, there was strong Bayesian evidence against a (bidirectional) null hypothesis, $BF_{01} = 7.10$. The significant dependency in the data is consistent with holistic recollection and therefore strengthens our prediction that the EEG data from Experiment One will show incidental reinstatement of information about studied scenes even though memory for scene context is not tested in that task (to enable this incidental measure). The results of the two studies will therefore be complementary. The holistic theory also predicted that cueing would not reduce dependency, however this result can also be explained by the lack of a reliable overall cueing effect on either scene or format memory.

Conclusions and Recommendations

Recollecting the past involves selecting from a large number of stored memory traces. Here, we used EEG to investigate how and when people recover desired information. By measuring time-resolved neural responses during recollection, we were able to quantify pre-retrieval selection more directly than is possible with behavioural measures. Multivariate decoding approaches to electrophysiological data are now providing important new insights into the chronometry of recollection, in line with intracranial recordings from humans and animals³². The current project is to our knowledge the first to apply multivariate decoding as well as standard univariate ERP analysis to study selective recollection, and our results converge with those from other labs who have successfully decoded retrieval goals³³ and demonstrated complementary evidence for encoding specificity theory²⁷. The results thus provide new knowledge about psychophysiological processes supporting recollection, and insights into how goals shape recollection as it emerges in real-time.

Our main findings already suggest several promising avenues for new research. Together, the univariate and multivariate results from Experiment Two and its companion study provide initial evidence for a multi-stage model of pre-retrieval memory selection. We will put this model to test in planned work involving fMRI brain imaging as well as electrophysiology to refine knowledge of where in the brain, as well as when, selection is implemented. The preparatory cue data also offer the first direct support for the long-hypothesized process of partial mental reinstatement of representations that are currently targeted in memory. Such mental reinstatement is thought to generate an effective 'internal' memory cue and instructions thought to engender it are used by police to guide eyewitness memory. In future work we will investigate whether goal-directed mental reinstatement predicts memory trial by trial. We will also apply the methods developed here to ask whether reduced selection ability explains poorer memory in older adults who have reduced cognitive control, as we have previously proposed^{34,35}, and provide novel and important tests of the longstanding hypothesis that older people's memory will benefit more than young people's memory from 'environmental support' given the right external cues³⁵.

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