The effect of repetition priming on implicit recognition memory as measured by Fast Periodic Visual Stimulation and EEG

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ABSTRACT

Introduction: The development of rapid and reliable neural measures of memory is an important goal of cognitive neuroscience research and clinical practice. Fast Periodic Visual Stimulation (FPVS) is a recently developed electroencephalography (EEG) method that involves presenting a mix of novel and previously-learned stimuli at a fast rate. Recent work has shown that implicit recognition memory can be measured using FPVS, however the role of repetition priming remains unclear. Here, we attempted to separate out the effects of recognition memory and repetition priming by manipulating the degree of repetition of the stimuli to be remembered.

Method: Twenty-two participants with a mean age of 20.8 (± 4.3) yrs completed an FPVS-oddball paradigm with a varying number of repetitions of the oddball stimuli, ranging from repetition only (pure repetition) to no repetition (pure recognition). In addition to the EEG task, participants completed a behavioural recognition task and visual memory subtests from the Wechsler Memory Scale – 4th edition (WMS-IV).

Results: An oddball memory response was observed in all four experimental conditions (pure repetition to pure recognition) compared to the control condition (no oddball stimuli). The oddball memory response was largest in the pure repetition condition and smaller, but still significant, in conditions with less/no oddball repetition (e.g. pure recognition). Behavioural recognition performance was at ceiling, suggesting that all images were encoded successfully. There was no correlation with either behavioural memory performance or WMS-IV scores, suggesting the FPVS-oddball paradigm captures different memory processes than behavioural measures.

Conclusion: Repetition priming significantly modulates the FPVS recognition memory response, however recognition is still detectable even in the total absence of repetition priming. The FPVS-oddball paradigm could potentially be developed into an objective and easy-to-administer memory assessment tool.

Keywords: Recognition memory; Repetition Priming; Oddball; EEG; Visual Evoked Potentials; Fast Periodic Visual Stimulation

1 Introduction

Recognition memory is a form of explicit or declarative memory critical to daily functioning. We rely on recognition memory when performing many everyday tasks (e.g., recognising items that we need to buy when walking around a supermarket) and social interactions (e.g. recognising a friend passing by when walking down the street and greeting them). This type of memory is crucial to our independent daily functioning and involves two distinct processes: familiarity and recollection (Yonelinas, 2002). Familiarity is a rapid process that occurs on a spectrum, ranging from a weak intuition to a strong belief. For example, when someone greets you and you have a strong feeling of knowing who this person is, but you cannot recall who they are, how you know them or exactly where you met them. On the other hand, recollection is the process of making associations of different pieces of information about a person or object based on a cue. For example, as you talk to someone that is familiar to you, information about this person aggregates until a threshold is reached and conscious recollection occurs.

An important concept in recognition memory is repetition priming (hereafter referred to as priming), which is defined as a long lasting change in the processes of identifying, producing or detecting an item, as a consequence of previous exposure to that item (Berry, Shanks, Speekenbrink, & Henson, 2012). According to the multiple systems theory, recognition and priming are distinct at both a functional and neural level (Squire, 1992, 2009; Squire & Dede, 2015). In contrast, the single-system theory suggests recognition and priming are driven by a unitary memory signal. The relationship between explicit memory (recognition) and implicit memory (priming) has been a significant focus of research (Addante, 2015; Berry et al., 2012; Hannula & Greene, 2012; Lucas, Taylor, Henson, & Paller, 2012; Shanks & Berry, 2012; Squire, 1992, 2009; Squire & Dede, 2015) and there is still no clear consensus on whether these processes are distinct at a neural level or supported by a single memory system. However, some recent studies have provided evidence supporting the single-system theory. For example, Addante's (2015) re-analysis of their event-related potential (ERP) study used a procedure that controlled for explicit memory differences. This procedure involved

contrasting ERPs as a function of the old/new status of the item while recognition confidence was controlled for (see Yu and Rugg (2010) for more details on this procedure). They reported that, at a neurophysiological level, amnesia patients were impaired in implicit memory compared to controls. These findings suggest that explicit and implicit memory may rely on a single neural source but have different physiological functions. Furthermore, Berry et al.'s (2012) exploration of modelling frameworks of recognition and priming revealed that the single-system model was able to predict several behavioural recognition results more consistently than multiple systems models. Moreover, in a behavioural study investigating repetition priming and recognition memory in amnesia patients, a single-system model predicted numerous results for amnesia patients better than two different multiple-systems models (Berry, Kessels, Wester, & Shanks, 2014). These findings provide evidence for the single-system model over multiple-systems models, suggesting a reduction in the strength of a single memory signal underpins the impairments seen in recognition and priming in amnesia.

Neural measures of cognition provide objective measures that can help us directly compare multiple- and single-system theories of memory (Addante, 2015; Lucas et al., 2012). However, a major challenge in this field has been the difficulty of finding tasks that can reliably measure the processes underlying priming and recognition distinctly. For example, in most ERP studies, the tasks used make it very difficult to measure the effect of repetition priming without measuring familiarity (Henson, Hornberger, & Rugg, 2005; Lucas et al., 2012; Yu & Rugg, 2010). Additionally, the findings of studies supporting the multiple-systems theory have often failed to replicate (see Berry et al. (2012) for an in-depth review).

Recently, a new electroencephalography (EEG) technique, Fast-Periodic-Visual-Stimulation (FPVS), has enabled reliable assessment of cognitive performance due to its very high signal to noise ratio (SNR) (Heinrich, Mell, & Bach, 2009; Rossion, 2014; Rossion, Torfs, Jacques, & Liu-Shuang, 2015; Stothart, Quadflieg, & Milton, 2017; Stothart, Smith, & Milton, 2020). This technique involves presenting a large number of stimuli at a rate that allows for visual processing, but is too fast to allow participants to respond behaviourally. In an FPVS-oddball

paradigm, oddball stimuli are embedded in a stream of standard stimuli at fixed intervals with set presentation frequencies for each type of stimuli (see Figure 1). The outcome measure of this paradigm is an increase in EEG signal at the same frequency of the oddball stimulus presentation. These properties mean that the FPVS technique is uniquely positioned to provide insight into neural activity evoked by implicit recognition memory without participants having to respond in any way or even comprehend the task.

Figure 1. An illustration of the standard image (S) and oddball image (O) presentation frequencies. F refers to the standard image presentation rate (e.g. 3 Hz) and f refers to the oddball image presentation rate (e.g. 0.6 Hz).

Using a similar paradigm to that shown in Figure 1, Stothart et al. (2020) demonstrated that FPVS could be used to measure implicit recognition memory. Participants were given eight images to learn during a pre-FPVS encoding phase to ensure successful recognition. To allow for an FPVS stimulation sequence of 3 minutes oddball images had to be repeated 13 times during the FPVS task. An active control condition was included in which oddball stimuli were repeated during the FPVS presentation, but without a pre-FPVS encoding task. A neural

response to the oddball stimuli that were previously encoded was observed, suggesting that FPVS is able to detect neural markers of recognition. However, an oddball response was also observed in the active control condition (in the absence of a pre-task encoding phase), making it difficult to identify the extent to which the oddball signal was evoked by the initial encoding of oddball images and their repeated presentation within the task itself (i.e., effect of priming). Therefore, in this study, we aimed to disentangle the factors contributing to the implicit recognition response by varying the degree of oddball repetition from pure repetition to no repetition (pure recognition). Based on the single-system theory (which holds that a single, continuous memory signal subserves recognition and priming), we predicted that participants' implicit recognition memory, as indexed by their neural responses to oddball stimuli, would decrease as oddball repetition reduced.

2 Material and methods

2.1 Participants

22 young adults (aged 18-35, mean age 20.77 (± 4.30), 10 males) participated in this study. All participants were undergraduate students recruited from the University of Bath and they all declared themselves to be in good general health with normal or corrected-to-normal vision. Ethical approval for all procedures were obtained from the University of Bath Psychology research ethics committee. Participants provided written informed consent before participating and were free to withdraw from the study at any time.

2.2 Design

A within-subjects repeated measures design was used to investigate the effect of oddball image repetition on the EEG FPVS-oddball response. The independent variable was experimental condition (four conditions with varying numbers of oddball images (1, 8, 36, 72), with no image repetition in the fourth condition, as well as a control condition without any oddball images (Table 1). The control condition provided a within-subject measure of

background neural activity at oddball frequencies, against which oddball frequencies in the experimental conditions could be compared. The dependent variable was the mean SNR of the oddball frequency and its significant harmonics, f_+ .

2.3 Stimuli

All images used in this experiment were chosen from the Bank of Standardised Stimuli v2.0 (Brodeur, Guerard, & Bouras, 2014), a validated set of 1,468 high quality colour images. Image features were as follows: 512x512 pixels, 96dpi, subtending 10° visual angle. Each image was only used once, i.e., either as a standard, oddball or foil (see Figure 2 for an example of the images used in this study).

Figure 2. Fast Periodic Visual Stimulation (FPVS)-oddball recognition memory task procedure. **a)** oddball image encoding stage (e.g. guitar) - each image is presented once for 3 seconds, followed by a two alternative forced choice task to ensure participants have paid attention to and encoded each oddball image. **b)** FPVS task - the oddball image encoded earlier is embedded in a stream of novel standard images at a fixed frequency (oddball image presentation frequency, f : 0.6 Hz; standard image presentation frequency, F : 3 Hz). **c)**

behavioural recognition memory task (Yes/No), where participants respond with 'Yes' for previously seen (i.e. oddball) images and 'No' for unseen images.

2.3.1 Standards

Standard stimuli were randomly selected. Each image was only presented once, with 288 unique images used in each of the five conditions.

2.3.2 Oddballs

Oddball stimuli were pre-selected for each of the four experimental conditions and were kept consistent across participants. The number of unique oddball stimuli varied across conditions, see Table 1. Equal numbers of natural and non-natural objects were pre-selected in order to ensure no systematic semantic categorical difference between standard and oddball stimuli.

2.3.3 Foils

For the two alternative forced choice (2AFC) task used in the pre-FPVS encoding phase, an equal number of images were pre-selected as foils to match the number of oddball images in each experimental condition (i.e., 1, 8, 36 and 72) and were kept consistent across participants. For the behavioural recognition tasks, 8 previously unseen images were randomly selected as foils for conditions two, three and four. For conditions three and four a random subset of 8 oddball images were selected.

Conditions	# of standard images	# of unique oddball stimuli	# of repetition of oddballs
Pure repetition (C1)	288	1	72
High repetition/low recognition (C2)	288	8	9
High recognition/low repetition (C3)	288	36	2
Pure recognition (C4)	288	72	1
Control	360	0	0

Table 1: Standard and oddball image numbers and oddball image repetition numbers per condition. Conditions one to four contained 72 loops of four standard images and one oddball image, whereas the control condition contained 72 loops of five standard images.

2.4 Procedure

Participants completed four experimental conditions with varying numbers of oddball images (1, 8, 36 and 72) and a control condition (no oddball images). Prior to the FPVS task in each condition, there was an encoding phase, where participants viewed all oddball images in a 2AFC task, see Figure 2. Participants were seated ~70 cm from the monitor.

2.4.1 Encoding stage

In the encoding phase, participants were asked to identify each image by naming them out loud, while it was presented for 3 seconds. After naming the image, the oddball image was presented alongside a foil. Participants were asked to indicate which image they had just seen using the left or right arrow keys. This procedure was repeated for each oddball image. The location in which the oddball stimuli appeared on the screen was pseudo-randomised to ensure images were presented equally often on either side of the screen. The encoding task was immediately followed by the FPVS task. There was no encoding stage for the control condition due to the lack of any oddball images to learn.

2.4.2 Fast Periodic Visual Stimulation

Participants were asked to focus on the centre of the screen, where the images appeared. To avoid lapses of attention and ensure participants were looking at the correct part of the screen, a fixation cross task was embedded within the FPVS task. This involved pressing a key when the centrally presented fixation cross turned from black to red in a random selection of 10% of the trials and lasted for 1.66s (the duration of the trial). Each trial consisted of 5 images - the first four were standard images and every fifth image was an oddball image, see Figure 1. Images were presented onscreen for 166ms with an inter-stimulus interval of 166ms. An example of a trial is presented in Figure 2b. Each standard stimulus was randomly selected from the standard image pool and was only presented once. Each oddball stimulus was presented a different number of times, depending on the experimental condition (see Table 1). In total, 360 images were presented in each condition, lasting approximately 120 seconds. The order of conditions was counterbalanced using a balanced Latin square design. This experimental design elicits two distinct steady state responses at 3 Hz and 0.6 Hz reflecting processing of the standard and oddball stimuli, respectively (Stothart et al., 2020).

2.4.3 Recognition task

For conditions 2-4, participants were asked to complete a behavioural recognition memory task. Participants were presented with 16 images sequentially and asked to indicate whether they had seen the image before or not (Yes/No response).

2.5 EEG recording

EEG signals were sampled at 1000 Hz from 65 channel HydroCel Geodesic Sensor Net electrodes using a GES 400 system (Electrical Geodesics Inc; EGI, Eugene, OR, USA), with a common Cz reference and online low pass filtered at 250 Hz. Impedances were below 50k Ω . Recordings were analysed offline using Brain Electrical Source Analysis software v5.3 (BESA

GmbH), MATLAB (MathWorks Inc.) and the Fieldtrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011). Blinks and eye movement artifacts were corrected using BESA automatic artifact correction (Berg & Scherg, 1994).

2.6 EEG analysis and steady state response

Data were re-referenced offline to a common average reference, downsampled to 256 Hz, and two electrooculogram electrodes were excluded from further analysis. To avoid aliasing artifacts an 85 Hz 24 dB zerophase lowpass filter was applied. The steady-state response was calculated according to the procedures described in Stothart et al. (2017). Epochs from 0 to 120s around trial onset were defined for each condition. This epoch length represents an integer number of cycles (72) of the oddball stimulus (0.6 Hz) ensuring that a frequency bin corresponding to the exact oddball frequency and its harmonics, including the standard frequency (3 Hz), were created. The frequency resolution was .0083 Hz. Epochs were first linearly de-trended, and the DC component was removed. As we used single epochs of a long duration, visual inspection revealed occasional instances of gross artifacts, e.g. large physical movement artifacts. Any artifact $\pm 250\mu\text{V}$ was removed from the data and replaced with zeros. To avoid discontinuities in the remaining data, data on either side of any removed section was tapered to zero using half a hanning window over 670 points of data. Across participants, the mean percentage of data removed by this procedure was 0.4%, 0.4%, 0.2% and 0.4% in the pure repetition condition (C1) and C2-C4, respectively, and 0.2% in the control condition. One participant in C3 had an excessively noisy recording with 39.9% of their data removed, as such, their data for C3 was removed and replaced by the group mean. For each participant and each electrode, amplitude was computed on these windows using the fast Fourier transform (FFT). SNR was then calculated by dividing the amplitude in each frequency bin by the mean amplitude of surrounding bins within a ± 0.10 Hz range (17 frequency bins) (Alp, Kogo, Van Belle, Wagemans, & Rossion, 2016; Srinivasan, Russell, Edelman, & Tononi, 1999; Stothart et al., 2017; Stothart et al., 2020) excluding the immediately adjacent bins (first

neighbouring bin on each side). Excluding the immediately adjacent bins from this correction meant that the amplitude correction was less likely to include any spread of the signal to proximal frequency bins (e.g. for 0.6 Hz adjacent bins were 0.5941 & 0.6059 Hz).

Previous research has shown a robust steady state visually evoked potential (SSVEP) response to the oddball frequency and many of its harmonics (Norcia, Appelbaum, Ales, Cottareau, & Rossion, 2015; Rossion et al., 2015), with oddball detection more reliably and accurately measured when including the harmonics of the oddball response (Stothart et al., 2017; Stothart et al., 2020). Consequently, the SNR was calculated for 2 values: the standard frequency F (3 Hz) and the mean of the oddball frequency and significant harmonics f_+ . To identify which harmonics to include in the calculation of f_+ , group Z scores were calculated for each harmonic (based on the global average of all electrodes averaged across the five conditions) relative to the neighbouring frequency bins within a ± 0.10 Hz range. This identified the highest significant harmonic ($Z > 1.645$) at 3 Hz across the four experimental conditions (see Supplementary Table 1), therefore for further analyses f_+ was always calculated as the mean SNR of 0.6, 1.2, 1.8 and 2.4 Hz. These values were calculated for each participant and electrode for all five conditions.

All analysis code used here is freely available and modifiable through the Fastball toolbox, <https://gsthart.github.io/Fastball/> and our pre-registration document can be found on the Open Science Framework (<https://osf.io/zd26y/>).

2.7 Standardised Memory Assessment tool – Wechsler Memory Scale 4th Edition

A standardised memory assessment tool, Wechsler Memory Scale – 4th Edition (WMS-IV), was used to test for correlations between visual memory and the EEG FPVS-oddball response, as well as confirm the population validity of our sample (Wechsler, 2009). Three

subtests from the WMS-IV were administered: the Symbol Span and Visual Reproduction I and II subtests.

Symbol Span (SS) assesses visual working memory using novel visual stimuli. Visual Reproduction I (VRI) assesses memory for non-verbal visual stimuli with an immediate recall task. Visual Reproduction II (VRII) is a delayed recall task for stimuli learned in VRI. VRII assesses long-term visuospatial memory with free recall and recognition tasks.

Scaled scores were calculated using the WMS-IV manual's age-matched normative data (Wechsler, 2009).

2.8 Statistical analyses

A repeated measures ANOVA was used to determine the effect of experimental condition on the scalp averaged EEG FPVS-oddball response. A two-way 3 (Region of interest (ROI)) x 5 (Condition) repeated measures ANOVA was used to investigate the effect of ROI and condition on the oddball response. Bonferroni correction was used to control for multiple comparisons.

Behavioural recognition performance was compared using Friedman's test since the data violated the parametric assumptions required for ANOVA. Neuro-behavioural correlations between the EEG FPVS-oddball response and WMS-IV scores were investigated using a Pearson's correlation and a Spearman's rho was used to investigate correlations with the behavioural recognition task since the data was non-parametric.

3 Results

3.1 Task compliance and attention during the FPVS task

There were no systematic differences in reaction time between the conditions suggesting that participants engaged equally with each condition (C1: $M = 647$ ms ($SD = 123$); C2: $M = 626$ ms ($SD = 190$); C3: $M = 669$ ms ($SD = 281$); C4: $M = 632$ ms ($SD = 191$); Control: $M = 573$ ms ($SD = 103$); $F(1.65, 32.97) = 0.71$, $p = .472$, $\eta_p^2 = .034$). Participants were also equally accurate in detecting fixation cross colour changes across the five conditions (average of 6 out of 7 correctly identified across all conditions), $F(4,80) = 0.28$, $p = .890$).

3.2 The influence of stimulus repetition on recognition oddball responses

Figure 3 demonstrates the scalp-averaged SNR averaged across participants for the five conditions. A repeated measures ANOVA with five levels of condition revealed a significant difference in the SNR of scalp-averaged $f+$ between conditions, $F(2.36,49.52) = 24.59$, $p < .001$, $\eta_p^2 = .539$. The scalp-averaged $f+$ during the control condition was significantly lower than during conditions 1, 2 and 4; however, there was no difference between the control condition and condition 3, see Table 2 for within-subjects simple contrasts of experimental condition vs control.

Condition (vs Control)	Mean	95% Confidence Interval	p	η_p^2
Pure repetition (C1)	1.58	1.41, 1.74	< .001	.673
High repetition/low recognition (C2)	1.24	1.14, 1.34	.002	.365
High recognition/low repetition (C3)	1.11	1.05, 1.17	.136	.103
Pure recognition (C4)	1.15	1.09, 1.22	.026	.215
Control	1.06	1.01, 1.11		

Table 2: Comparison of scalp averaged $f+$ of SNR for each condition against the control condition.

315

316 **Figure 3:** Spectral plots showing the SNR of the oddball frequency (0.6 Hz), its significant harmonics (1.2 Hz, 1.6 Hz, 2.4 Hz) and the standard
 317 image presentation rate (3 Hz) of the five conditions, averaged across the scalp (63 electrodes) and participants (N = 22) – top row. Oddball
 318 frequency (f , 0.6 Hz) and harmonics Topographic plots (bottom row) illustrate the SNR of f in each of the five conditions.

Topographic plots presented in Figure 3 demonstrate the difference in SNR of $f+$ for each condition. Signal strength was greater in conditions with higher oddball repetition and gradually decreased as oddball repetition decreased. Notably, there appeared to be three major regions of activation: left occipito-parietal (centred around P7), right occipito-parietal (centred around P8) and central/vertex (centred around Cz). Furthermore, central/vertex activation reduced as oddball repetition decreased, whereas bilateral occipito-parietal activation persisted.

The absence of an oddball response in C3, but presence in C4, was not expected. Therefore, to further explore the topographic differences between the conditions, a more sensitive ROI analysis was performed. The ROI analysis focused on three neighbouring electrodes around P7 (left occipitoparietal; 29, 30, 32), P8 (right occipitoparietal; 43, 44, 47) and Cz (central/vertex; 63, 4, 7) regions for each condition. The results of these analyses are presented in Figure 4. A two-way (ROI (3 levels) x Condition (5 levels)) repeated measures ANOVA was used to investigate the effect of ROI and condition on the ROI $f+$ values calculated as a mean of the three electrodes from each region. This analysis revealed a significant effect of condition on the oddball response wherein the group-level $f+$ SNR of all experimental conditions was significantly higher than for the control condition. These results are reported in detail in Table 3.

The ROI analysis revealed that the right occipitoparietal region nearly showed a consistent significant oddball response, left occipitoparietal region showed a significant oddball response when there was a relatively high level of oddball repetition and the central/vertex region only showed a significant oddball response to pure repetition. Whether the lack of a significant oddball response in conditions with lower repetition (e.g., C3 and C4) was due to distinct neural sources for repetition and recognition, or a result of poor signal strength remains unclear.

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345 **Figure 4:** Violin plots of f^+ calculated for each condition and ROI. Tukey boxplots reflect the median and inter-quartile ranges, width of the violin

346 plots reflects kernel density estimated using MATLAB's ksdensity function.

a) Main Effects				
	df	<i>F</i>	<i>p</i>	η_p^2
Condition (C1, C2, C3, C4, Control)	2.4, 50.4	35.3	<.001	.627
ROI (Left Occipitoparietal, Right Occipitoparietal, Central)	1.4, 30.2	3.4	.062	.138
Group x ROI	4.5, 95	3	.017	.126
b) Condition effects				
Condition (vs Control)	Mean Difference <i>f+</i>	95% CI	<i>p</i>	η_p^2
Pure repetition (C1)	0.97	0.74, 1.21	<.001	.781
High repetition/low recognition (C2)	0.36	0.21, 0.52	<.001	.536
High recognition/low repetition (C3)	0.13	0.04, 0.23	.009	.285
Pure recognition (C4)	0.19	0.05, 0.32	.008	.289

c) Post-hoc analyses of ROI x Condition interaction

	Pure repetition (C1) vs Control			High repetition/low recognition (C2) vs Control			High recognition/low repetition (C3) vs Control			Pure recognition (C4) vs Control		
	Mean difference <i>f+</i> (95%CI)	<i>p</i>	Cohen's <i>d</i>	Mean difference <i>f+</i> (95%CI)	<i>p</i>	Cohen's <i>d</i>	Mean difference <i>f+</i> (95%CI)	<i>p</i>	Cohen's <i>d</i>	Mean difference <i>f+</i> (95%CI)	<i>p</i>	Cohen's <i>d</i>
Left Occipitoparietal	0.77 (0.53, 1.01)	<.001	1.14	0.26 (0.10, 0.42)	.003	0.59	0.10 (-0.08, 0.28)	.240	0.21	0.25 (0.09, 0.41)	.003	0.62
Right Occipitoparietal	1.15 (0.77, 1.54)	<.001	0.99	0.60 (0.35, 0.86)	<.001	0.77	0.23 (0.04, 0.43)	.021	0.43	0.26 (0.07, 0.44)	.009	0.50
Central (Vertex)	1.00 (0.79, 1.21)	<.001	1.81	0.23 (0.06, 0.40)	.011	0.50	0.06 (-0.09, 0.21)	.421	0.17	0.06 (-0.12, 0.24)	.500	0.12

Table 3 a) Results of the 2-way (ROI (3-levels) x Condition (5-levels)) repeated measures ANOVA demonstrating the main effects of condition and ROI on oddball *f+* responses. **b)** Pairwise comparisons of the effect of Condition alone on oddball *f+* responses. Values in bold indicate significant differences after Bonferroni correction of .05/4= .013. **c)** Post-hoc pairwise comparisons of the ROI x Condition interaction. Values in bold indicate significant differences after Bonferroni correction (.05/12= .004). Cohen's *d* was calculated using the effect size estimates in the repeated measures designs tool developed by (Lenhard & Lenhard, 2016). The other effect sizes are reported as partial eta squared (η_p^2).

3.3 Behavioural recognition memory response

Participants' behavioural recognition performance was analysed using d prime (d') (see Figure 5), a metric based on the difference between the z scores of hits and false alarms in the recognition memory task. d' was calculated using the following formula:

$$d' = z(H) - z(FA)$$

Where H (Hit) is the number of correctly identified 'seen' images during the recognition memory task and FA (False Alarm) is the number of 'unseen' images falsely identified as a previously 'seen' image (Snodgrass & Corwin, 1988; Stanislaw & Todorov, 1999). A higher d' prime score equates to better recognition.

Figure 5: Violin plots demonstrating the behavioural recognition memory (Yes/No) task d' scores for the conditions with 8 or more oddball images (C2-C4). Tukey boxplots reflect the

median and inter-quartile ranges, whereas width of the violin plots reflects kernel density estimated using MATLAB's ksdensity function.

The difference in oddball object recognition was analysed using the Friedman test, which revealed a statistically significant difference between the mean ranks of d' between conditions C2, C3 and C4, $\chi^2(2) = 7.302$, $p = .026$. However, post-hoc pairwise comparisons showed no significant differences between conditions (C2-C3 $p = .874$; C2-C4 $p = .179$; C3-C4 $p = 1.000$).

3.4 Wechsler Memory Scale – IV performance

Z Scores were calculated from Scaled Scores for the purpose of visualising performance across tasks (see Figure 6).

Figure 6: Violin plots illustrating the z scores of participants' performance on the four WMS-IV tasks. SS: Symbol Span, VR Immediate: Visual Reproduction Immediate Recall, VR Delayed: Visual Reproduction Delayed Recall, VR Recog: Visual Reproduction Recognition.

Participants' mean ($\pm$ SD) subtest scaled scores were: SS = 10 $\pm$ 1.91, VRI = 10.77 $\pm$ 2.0 and VRII = 11.95 $\pm$ 3.18. These scaled scores suggest that our sample's scores were at the 50th percentile (Average) for SS and VRI and 75th percentile (High Average) for the VRII subtest of the normative sample. VR recognition cumulative percentages of our sample were mostly within the highest percentage band of >75 (High Average), although some participants were in the 26-50 (Average) percentage band (Wechsler, 2009).

3.5 Neuro-behavioural correlations

The WMS-IV subtest scaled scores did not correlate with the scalp averaged f_+ SNR of the pure recognition condition (C4) (SS: $r = -.043$, $p = .425$; VRI: $r = -.264$, $p = .118$; VRII: $r = -.133$, $p = .277$), high recognition condition (C3) (SS: $r = -.073$, $p = .374$; VRI: $r = .011$, $p = .481$; VRII: $r = -.111$, $p = .311$) and high repetition condition (C2) (SS: $r = .121$, $p = .296$; VRI: $r = -.079$, $p = .363$; VRII: $r = -.046$, $p = .420$).

The behavioural recognition d' did not correlate with the scalp averaged f_+ SNR of the pure recognition condition (C4) ($r = .078$, $p = .730$) and high recognition condition (C3) ($r = .304$, $p = .169$). However, there was a significant positive correlation between the scalp-averaged f_+ SNR of the high repetition condition (C2) and the behavioural recognition d' of this condition ($r = .535$, $p = .010$).

4 Discussion

4.1 Summary of key findings

This study investigated whether the extent to which the FPVS response to oddball stimuli reflects recognition or repetition priming by manipulating the degree of repetition of the oddball stimuli from pure repetition to no repetition. In line with our hypothesis, oddball responses were greatest in conditions with the highest level of repetition priming (C1 and C2) and lower in conditions with very little or no priming (C3 and C4). When averaged across the scalp, oddball responses were observed in the pure repetition (C1), high repetition/low recognition (C2) and pure recognition (C4) conditions, however no significant oddball response was observed in the low repetition/high recognition (C3) condition. A region of interest analysis however showed significant oddball responses in all experimental conditions (C1-C4) compared to the control condition. This highlights that when the oddball response was weaker (e.g. in C3) scalp average measures were not sufficiently sensitive to capture the response. We propose that responses to C3 were not qualitatively different from that of C4, rather they were both weak, on the margins of detection, and in future best suited to *a priori* ROI measurement.

Oddball responses were strongest at the vertex and bilateral occipitoparietal regions. Responses at the vertex were strongest in the pure repetition condition and absent in the pure recognition condition, with occipito-parietal activation present across all experimental conditions. This pattern supports previous reports of distinct scalp topographies of repetition and familiarity-driven recognition responses and the involvement of parietal and mid-frontal regions in these processes (Fiebach, Gruber, & Supp, 2005; Yu & Rugg, 2010). Due to the limited spatial resolution of EEG, it is difficult to confidently say whether these findings provide evidence for the multiple-process theory. Future studies should examine the neural sources of this dissociation in order to establish whether this topographic difference reflects differing neural sources for repetition detection and recognition, or simply greater response magnitudes in the pure repetition condition.

Overall, the findings extend our understanding of the effect of repetition in FPVS recognition memory oddball responses by showing that while repetition priming plays a significant role in enhancing the oddball response, it is not the sole driver of the response, as oddball responses were observed in the complete absence of repetition priming (in C4).

4.2 Pure repetition and pure memory signals

The effect of oddball image repetition (priming) was prominent in the scalp averaged recognition memory response. One of the critical questions remaining from Stothart et al. (2020) was whether recognition memory could be measured using FPVS in the absence of repetition priming. Our scalp and ROI averaged findings confirm this is possible, but that the oddball response is significantly weakened.

The pure repetition condition (C1) evoked the strongest oddball signal compared to the other conditions with lower levels of oddball repetition. A number of factors may result in this augmentation of the oddball response. A possible explanation, stemming from single-system theory, is that repetition priming strengthens the memory of the image learned in the encoding phase (Park & Donaldson, 2016). This happens through repeated exposure to oddball images that leads to an increase in the strength of the memory signal driving recognition and priming (Berry et al., 2012). Another possible driver of the repetition response could be statistical learning (Mandikal Vasuki, Sharma, Ibrahim, & Arciuli, 2017; Romberg & Saffran, 2010). For example, during the task participants may categorise stimuli into “repeating” and “non-repeating” classes or, alternatively, they could realise that four non-repeating images are followed by a fifth repeating image, also known as “chunking” (Dehaene, Meyniel, Wacongne, Wang, & Pallier, 2015). This online classification of oddball stimuli would result in predictive feedback and the classic visual mismatch response to oddball stimuli (Näätänen & Michie, 1979; Stefanics, Astikainen, & Czigler, 2014).

4.3 EEG recognition, behavioural recognition and WMS-IV visual memory responses

Behavioural recognition measures showed that participants had encoded oddball images successfully, as their post-FPVS behavioural recognition scores were near ceiling. Participants' WMS-IV scores were within normal ranges established in previous normative samples (Wechsler, 2009). However, there were also no correlations with performance on the visual memory subtests of the WMS-IV, suggesting the WMS-IV tasks and the FPVS task might be measuring different cognitive processes. Participants' implicit recognition memory, as a proxy of their oddball response measured by FPVS, was not correlated with the post-FPVS behavioural recognition measures in conditions with low repetition or no repetition (C3 and C4), though there was a significant correlation between the EEG measure and behavioural measure of the high repetition/low recognition (C2). However, future studies should further probe the relationship between f_+ and conscious recognition with more demanding behavioural tasks that avoid ceiling effects. Additionally, FPVS oddball response is a neural proxy measure of memory, potentially reflecting the early, automatic stages of recognition.

4.4 Clinical applications

Recognition memory is often impaired in neurological conditions such as mild cognitive impairment and Alzheimer's disease (Didic et al., 2011). Thus, the development of reliable and objective assessments of recognition memory is of great importance to inform diagnoses and enable disease monitoring. EEG is a non-invasive, objective, and more cost-effective potential diagnostic tool than neuroimaging techniques such as functional magnetic resonance imaging (MRI) and positron emission tomography (PET). Due to the nature of PET and MRI (which use ionising radiation and/or involve exposure to powerful magnetic fields), many older adults cannot undergo such scans due to contraindications (e.g., metal pins in the body). Moreover, even if there are no contraindications, many subjects find having an MRI scan

anxiety provoking and are reluctant to have one. Currently, the clinical use of EEG as a diagnostic tool for neurological disorders (e.g. epilepsy) and disorders of sleep and consciousness is through visual inspection of the EEG as a part of the patient's neurological assessment (Micanovic & Pal, 2014; Tan, Tung, Leong, & Than, 2012). Although visual inspection of the EEG has been a useful diagnostic tool, the utility of this method can be enhanced in numerous ways to increase its sensitivity and specificity in diagnosing neurological disorders such as Alzheimer's disease.

Measuring recognition memory implicitly is a great advantage of the FPVS method when it comes to its clinical applications, since it eliminates confounds such as slow motor or linguistic responses or motivational factors. Future research should investigate whether the FPVS technique is able to distinguish people with memory impairment (e.g. patients with Alzheimer's disease) from healthy controls.

4.5 Limitations and future research

One of the limitations of this study was that the fourth condition, C4 (72 images to be learned) was more demanding than C1 or C2 (1 or 8 images to be learned, respectively), raising the possibility that task difficulty could have underpinned the reduction in the oddball response as the number of images to be learned increased. However, performance was not significantly worse in the no-repetition condition (C4) than in the condition in which the images were repeated nine (C2) or two times (C3), suggesting that participants were able to encode and retain stimuli equivalently across these conditions.

When attempting to investigate the relationship between EEG and behavioural measures of recognition memory, we were not able to determine whether priming led to a speeding up of participants' reaction times (as suggested by Park & Donaldson (2016)), since participants were not instructed to respond as quickly as possible. In a future study, this limitation should

be addressed to be able to determine whether repetition priming during the FPVS task results in shorter reaction times in post-FPVS behavioural recognition.

A difference in topographical locations of the FPVS signal for pure repetition and pure recognition conditions suggests there might be different neural sources for these signals. Repeating the current study using functional neuroimaging techniques to identify the neural source(s) of the oddball response as a proxy of implicit recognition memory would be a valuable next step.

4.6 Conclusion

In this study, we provide further evidence that the FPVS technique can be used to measure recognition memory performance. Our findings shed light on issues surrounding the effect of oddball stimulus repetition on the memory response and demonstrate that the implicit recognition memory-related EEG signal is present even in the absence of oddball image repetition. We suggest two distinct avenues for future research: for cognitive neuroscientists, the next steps should be to identify the neural sources of the FPVS recognition memory signal, which would contribute to the debate regarding single versus multiple memory systems, and for clinical neuroscientists, the next steps should be to investigate the predictive utility of the FPVS recognition memory test as an early detection tool for neurological conditions associated with recognition memory impairment (e.g. Alzheimer's Disease).

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Supplementary Information

528 Supplementary Table 1: z score values of group and scalp average of SNR per condition for
 529 each multiple of the oddball frequency up to 30 Hz.

Frequency (Hz)	C1	C2	C3	C4	Control
0.6	3.9	3.6	0.7	0.9	0.7
1.2	11.1	3.6	1.3	0.7	-0.3
1.8	12.9	2.1	0.6	2.4	1.3
2.4	5.4	2.3	1.9	2.2	0.7
3	64.9	43.3	51.7	46.2	58.8
3.6	7.5	3.8	1.5	0.5	2.6
4.2	6.8	6.3	0.3	1.5	2.0
4.8	9.5	4.9	2.3	-0.2	-0.1
5.4	10.1	4.2	0.6	1.1	1.5
6	98.9	86.9	70.6	101.1	90.2
6.6	6.0	6.0	1.0	0.9	-1.3
7.2	6.2	0.7	1.2	1.1	-1.6
7.8	11.8	4.8	0.8	0.5	0.0
8.4	9.2	3.4	1.0	0.5	1.5
9	33.6	33.6	25.2	30.4	28.7
9.6	3.3	1.4	1.7	-1.6	1.4
10.2	4.9	-0.2	-0.8	-1.8	0.5
10.8	7.6	0.1	-0.7	-0.7	-1.1
11.4	4.7	1.4	0.1	0.6	-0.5
12	41.2	42.4	51.9	41.5	50.0
12.6	5.8	-0.6	-0.2	0.6	-0.4
13.2	10.9	0.8	-0.3	1.8	0.6
13.8	7.1	0.4	1.2	-1.1	0.5
14.4	5.7	0.5	-0.3	1.9	-0.1
15	41.4	30.2	33.3	34.7	38.4
15.6	2.8	1.1	-0.6	-0.9	-0.5
16.2	4.6	-0.1	0.6	-1.0	0.1
16.8	4.7	-1.2	-0.8	-0.7	0.8
17.4	1.9	-1.2	0.9	-0.6	-0.5
18	32.9	19.6	23.5	24.5	32.7
18.6	5.4	-1.3	0.8	1.7	-1.6
19.2	3.8	1.7	0.4	-1.6	1.8
19.8	3.1	1.3	0.4	1.3	-0.5
20.4	1.5	0.7	0.5	-0.1	0.0
21	19.0	21.7	30.9	32.5	21.3
21.6	0.5	2.1	-1.5	1.9	-0.6
22.2	0.9	0.7	-0.4	0.1	-1.2
22.8	2.4	0.3	-0.4	-1.3	0.2
23.4	-0.3	-1.5	-1.3	0.8	-0.6
24	18.0	22.0	12.6	26.2	19.0
24.6	1.7	0.8	1.3	1.2	-2.7
25.2	-0.1	1.0	1.1	1.8	-2.0
25.8	1.5	-0.5	-0.7	-0.4	0.0
26.4	-1.2	1.4	0.5	-1.5	0.4
27	9.5	7.0	7.5	7.2	12.3

27.6	1.5	0.4	-0.2	-1.1	-1.0
28.2	0.1	-0.1	-0.1	-0.8	-1.0
28.8	1.4	-2.4	2.0	1.5	-0.7
29.4	0.2	1.7	1.8	-0.4	-1.3
30	23.3	16.9	14.5	13.9	23.8

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