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1   The effect of repetition priming on implicit recognition memory as measured by

2   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-learnt 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 very high repetition to no repetition. 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 (very high repetition to no repetition) compared to the control condition (no oddball stimuli). The oddball memory response was largest in the very high repetition condition and smaller, but still significant, in conditions with less/no oddball repetition. 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

68   contrasting ERPs as a function of the old/new status of the item while recognition confidence

69   was controlled for (see Yu and Rugg (2010) for more details on this procedure). They reported

70   that, at a neurophysiological level, amnesia patients were impaired in implicit memory

71   compared to controls. These findings suggest that explicit and implicit memory may rely on a

72   single neural source but have different physiological functions. Furthermore, Berry et al.'s

73   (2012) exploration of modelling frameworks of recognition and priming revealed that the

74   single-system model was able to predict several behavioural recognition results more

75   consistently than multiple systems models. Moreover, in a behavioural study investigating

76   repetition priming and recognition memory in amnesia patients, a single-system model

77   predicted numerous results for amnesia patients better than two different multiple-systems

78   models (Berry, Kessels, Wester, & Shanks, 2014). These findings provide evidence for the

79   single-system model over multiple-systems models, suggesting a reduction in the strength of

80   a single memory signal underpins the impairments seen in recognition and priming in amnesia.

81   Neural measures of cognition provide objective measures that can help us directly compare

82   multiple- and single-system theories of memory (Addante, 2015; Lucas et al., 2012). However,

83   a major challenge in this field has been the difficulty of finding tasks that can reliably measure

84   the processes underlying priming and recognition distinctly. For example, in most ERP

85   studies, the tasks used make it very difficult to measure the effect of repetition priming without

86   measuring familiarity (Henson, Hornberger, & Rugg, 2005; Lucas et al., 2012; Yu & Rugg,

87   2010). Additionally, the findings of studies supporting the multiple-systems theory have often

88   failed to replicate (see Berry et al. (2012) for an in-depth review).

89   Recently, a new electroencephalography (EEG) technique, Fast Periodic Visual Stimulation

90   (FPVS), has been developed to enable reliable assessment of neural correlates of cognition

91   due to its very high signal to noise ratio (SNR) (Heinrich, Mell, & Bach, 2009; Rossion, 2014;

92   Rossion, Torfs, Jacques, & Liu-Shuang, 2015; Stothart, Quadflieg, & Milton, 2017; Stothart,

93   Smith, & Milton, 2020). This technique involves presenting a large number of stimuli at a rate

94   that allows for visual processing, but is too fast to allow participants to respond behaviourally.

95 In an FPVS-oddball paradigm, oddball stimuli are embedded in a stream of standard stimuli

96 at fixed intervals with set presentation frequencies for each type of stimuli (see Figure 1). The

97 outcome measure of this paradigm is an increase in EEG signal at the same frequency of the

98 oddball stimulus presentation, reflecting a discrimination response between standard and

99 oddball stimuli.

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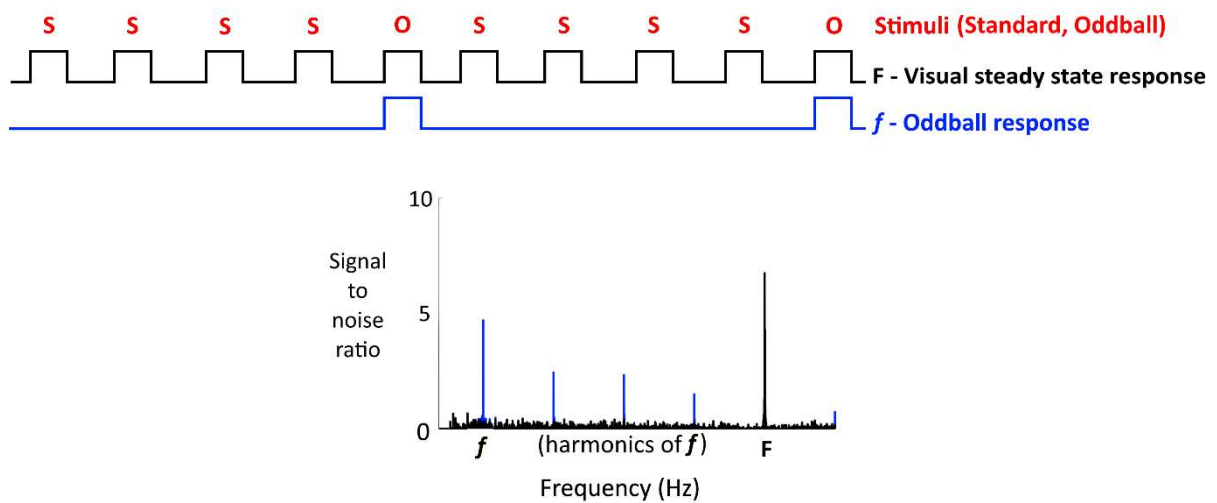
102

103 **Figure 1.** An illustration of the standard image (S) and oddball image (O) presentation

104 frequencies. **F** refers to the standard image presentation rate (e.g. 3 Hz) and f refers to the

105 oddball image presentation rate (e.g. 0.6 Hz).

106

107 Using a similar paradigm to that shown in Figure 1, Stothart et al. (2020) demonstrated that

108 FPVS could be used to measure implicit recognition memory. Participants were given eight

109 images to learn during a pre-FPVS encoding phase to ensure successful recognition. To allow

110 for an FPVS stimulation sequence of 3 minutes, oddball images had to be repeated 13 times

111 during the FPVS task. An active control condition was included in which oddball stimuli were

112 repeated during the FPVS presentation, but without a pre-FPVS encoding task. A neural

113 response to the oddball stimuli that were previously encoded was observed, suggesting that

114 FPVS is able to detect neural markers of implicit recognition. However, an oddball response

115 was also observed in the active control condition (in the absence of a pre-task encoding

116 phase), making it difficult to identify the extent to which the oddball signal was evoked by the

117 initial encoding of oddball images and their repeated presentation within the task itself (i.e.,

118 effect of priming). Therefore, in this study, we aimed to disentangle the factors contributing to

119 the implicit recognition response by varying the degree of oddball repetition from very high

120 repetition to no repetition.

121 The passive nature of the FPVS technique provides a unique insight into neural activity evoked

122 by implicit recognition memory without participants having to respond in any way or even

123 comprehend the task, i.e., it removes the need for measures of familiarity or recollection and

124 the engagement of conscious effort. In this context, FPVS oddball responses observed in the

125 current study will reflect the automatic and unconscious process that underlies familiarity, a

126 process that both multiple and single process theories of recognition memory propose. The

127 experimental manipulation of stimulus repetition adds further complexity to the responses,

128 with oddball responses in conditions with high levels of repetition likely reflecting not just the

129 automatic and unconscious process that underlies familiarity, but also perceptual priming and

130 explicit familiarity or even recollection.

131 We predicted that oddball responses reflecting the unconscious and automatic process

132 underling familiarity would be observed to previously seen and encoded oddball stimuli, and

133 that repetition of oddball stimuli would increase the magnitude of oddball responses.

134

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).
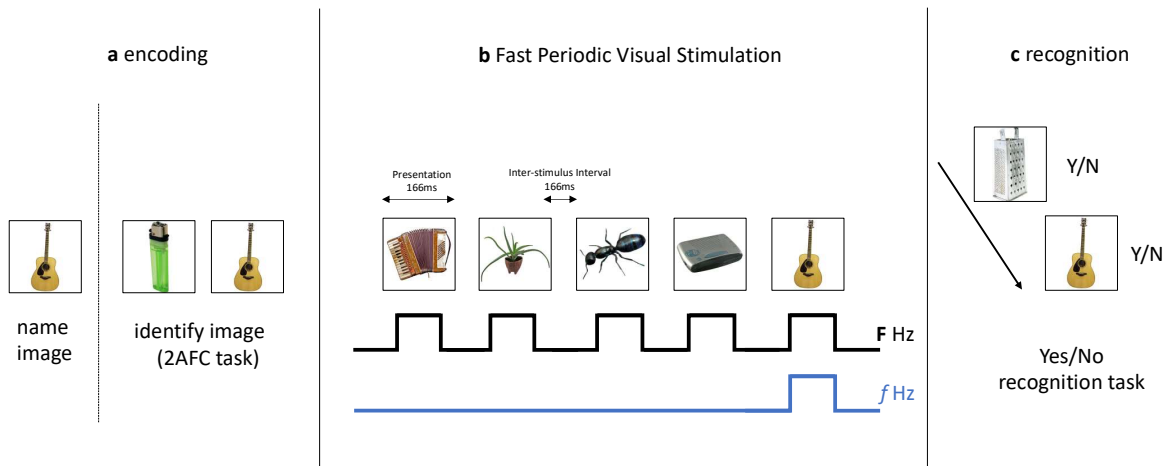
Figure 2. Fast Periodic Visual Stimulation (FPVS)-oddball recognition memory task procedure. **a)** oddball image encoding stage (e.g. guitar) - each image is presented once for 3 seconds, followed by a two alternative forced choice task to ensure participants have paid attention to and encoded each 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,

177 see Table 1. Equal numbers of natural and non-natural objects were pre-selected in order to

178 ensure no systematic semantic categorical difference between standard and oddball stimuli.

179

180 ### 2.3.3 Foils

181 For the two alternative forced choice (2AFC) task used in the pre-FPVS encoding phase, an

182 equal number of images were pre-selected as foils to match the number of oddball images in

183 each experimental condition (i.e., 1, 8, 36 and 72) and were kept consistent across

184 participants. For the behavioural recognition tasks, 8 previously unseen images were

185 randomly selected as foils for conditions two, three and four. For conditions three and four a

186 random subset of 8 oddball images were selected.

187

Conditions	# of standard images	# of unique oddball stimuli	# of repetition of oddballs
Very high repetition (C1)	288	1	72
High repetition (C2)	288	8	9
Low repetition (C3)	288	36	2
No repetition (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 50kΩ. Recordings were analysed offline using Brain Electrical Source Analysis software v5.3 (BESA

233   GmbH), MATLAB (MathWorks Inc.) and the Fieldtrip toolbox (Oostenveld, Fries, Maris, &

234   Schoffelen, 2011). Blinks and eye movement artifacts were corrected using BESA automatic

235   artifact correction (Berg & Scherg, 1994).

236

237   **2.6   EEG analysis and steady state response**

238   Data were re-referenced offline to a common average reference, downsampled to 256 Hz,

239   and two electrooculogram electrodes were excluded from further analysis. To avoid aliasing

240   artifacts an 85 Hz 24 dB zerophase lowpass filter was applied. The steady-state response was

241   calculated according to the procedures described in Stothart et al. (2017). Epochs from 0 to

242   120s around trial onset were defined for each condition. This epoch length represents an

243   integer number of cycles (72) of the oddball stimulus (0.6 Hz) ensuring that a frequency bin

244   corresponding to the exact oddball frequency and its harmonics, including the standard

245   frequency (3 Hz), were created. The frequency resolution was .0083 Hz. Epochs were first

246   linearly de-trended, and the DC component was removed. As we used single epochs of a long

247   duration, visual inspection revealed occasional instances of gross artifacts, e.g. large physical

248   movement artifacts. Any artifact +/-250uV was removed from the data and replaced with zeros.

249   To avoid discontinuities in the remaining data, data on either side of any removed section was

250   tapered to zero using half a hanning window over 670 points of data. Across participants, the

251   mean percentage of data removed by this procedure was 0.4%, 0.4%, 0.2% and 0.4% in the

252   very high repetition condition (C1) and C2-C4, respectively, and 0.2% in the control condition.

253   One participant in C3 had an excessively noisy recording with 39.9% of their data removed,

254   as such, their data for C3 was removed and replaced by the group mean. For each participant

255   and each electrode, amplitude was computed on these windows using the fast Fourier

256   transform (FFT). SNR was then calculated by dividing the amplitude in each frequency bin by

257   the mean amplitude of surrounding bins within a +/- 0.10 Hz range (17 frequency bins) (Alp,

258   Kogo, Van Belle, Wagemans, & Rossion, 2016; Srinivasan, Russell, Edelman, & Tononi,

259   1999; Stothart et al., 2017; Stothart et al., 2020) excluding the immediately adjacent bins (first

260   neighbouring bin on each side). Excluding the immediately adjacent bins from this correction

261   meant that the amplitude correction was less likely to include any spread of the signal to

262   proximal frequency bins (e.g. for 0.6 Hz adjacent bins were 0.5941 & 0.6059 Hz).

263

264   Previous research has shown a robust steady state visually evoked potential (SSVEP)

265   response to the oddball frequency and many of its harmonics (Norcia, Appelbaum, Ales,

266   Cottereau, & Rossion, 2015; Rossion et al., 2015), with oddball detection more reliably and

267   accurately measured when including the harmonics of the oddball response (Stothart et al.,

268   2017; Stothart et al., 2020). Consequently, the SNR was calculated for 2 values: the standard

269   frequency F (3 Hz) and the mean of the oddball frequency and significant harmonics f+. To

270   identify which harmonics to include in the calculation of f+, group Z scores were calculated for

271   each harmonic (based on the global average of all electrodes averaged across the five

272   conditions) relative to the neighbouring frequency bins within a +/- 0.10 Hz range. This

273   identified the highest significant harmonic (Z > 1.645) at 3 Hz across the four experimental

274   conditions (see Supplementary Table 1), therefore for further analyses f+ was always

275   calculated as the mean SNR of 0.6, 1.2, 1.8 and 2.4 Hz. These values were calculated for

276   each participant and electrode for all five conditions.

277   All analysis code used here is freely available and modifiable through the Fastball toolbox,

278   https://gstothart.github.io/Fastball/ and our pre-registration document can be found on the

279   Open Science Framework (https://osf.io/zd26y/).

280

281   **2.7   Standardised Memory Assessment tool – Wechsler Memory Scale 4th**

282   **Edition**

283   A standardised memory assessment tool, Wechsler Memory Scale – 4th Edition (WMS-IV),

284   was used to test for correlations between visual memory and the EEG FPVS-oddball

285   response, as well as confirm the population validity of our sample (Wechsler, 2009). Three

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

287 and II subtests.

288 Symbol Span (SS) assesses visual working memory using novel visual stimuli. Visual

289 Reproduction I (VRI) assesses memory for non-verbal visual stimuli with an immediate recall

290 task. Visual Reproduction II (VRII) is a delayed recall task for stimuli learned in VRI. VRII

291 assesses long-term visuospatial memory with free recall and recognition tasks.

292 Scaled scores were calculated using the WMS-IV manual's age-matched normative data

293 (Wechsler, 2009).

294

295 **2.8   Statistical analyses**

296 A repeated measures ANOVA was used to determine the effect of experimental condition on

297 the scalp averaged EEG FPVS-oddball response. A two-way 3 (Region of interest (ROI)) x 5

298 (Condition) repeated measures ANOVA was used to investigate the effect of ROI and

299 condition on the oddball response. Bonferroni correction was used to control for multiple

300 comparisons.

301 Behavioural recognition performance was compared using Friedman's test since the data

302 violated the parametric assumptions required for ANOVA. Neuro-behavioural correlations

303 between the EEG FPVS-oddball response and WMS-IV scores were investigated using a

304 Pearson's correlation and a Spearman's rho was used to investigate correlations with the

305 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 to fixation cross colour change 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 = 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
Very high repetition (C1)	1.58	1.41, 1.74	< .001	.673
High repetition (C2)	1.24	1.14, 1.34	.002	.365
Low repetition (C3)	1.11	1.05, 1.17	.136	.103
No repetition (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.

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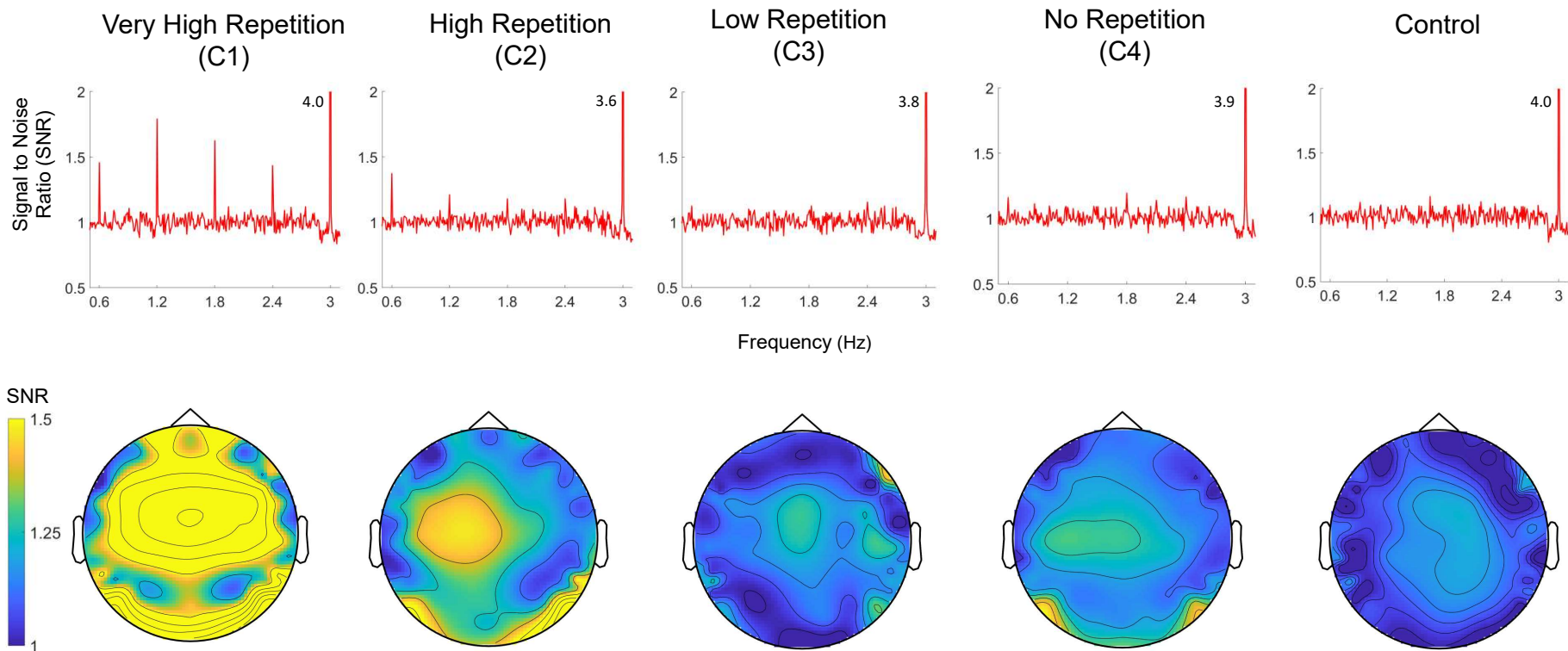
**Figure 3:** Spectral plots showing the SNR of the oddball frequency (0.6 Hz), its significant harmonics (1.2 Hz, 1.6 Hz, 2.4 Hz) and the standard image presentation rate (3 Hz) of the five conditions, averaged across the scalp (63 electrodes) and participants (N = 22) – top row. Oddball frequency (*f*;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

330 Topographic plots presented in Figure 3 demonstrate the difference in SNR of *f+* for each

331 condition. Signal strength was greater in conditions with higher oddball repetition and

332 gradually decreased as oddball repetition decreased. Notably, there appeared to be three

333 major regions of activation: left occipito-parietal (centred around P7), right occipito-parietal

334 (centred around P8) and central/vertex (centred around Cz). Furthermore, central/vertex

335 activation reduced as oddball repetition decreased, whereas bilateral occipito-parietal

336 activation persisted.

337 The absence of an oddball response in C3, but presence in C4, was not expected. Therefore,

338 to further explore the topographic differences between the conditions, a more sensitive ROI

339 analysis was performed. The ROI analysis focused on three neighbouring electrodes around

340 P7 (left occipitoparietal; 29, 30, 32), P8 (right occipitoparietal; 43, 44, 47) and Cz

341 (central/vertex; 63, 4, 7) regions for each condition. The results of these analyses are

342 presented in Figure 4. A two-way (ROI (3 levels) x Condition (5 levels)) repeated measures

343 ANOVA was used to investigate the effect of ROI and condition on the ROI *f+* values

344 calculated as a mean of the three electrodes from each region. This analysis revealed a

345 significant effect of condition on the oddball response wherein the group-level *f+* SNR of all

346 experimental conditions was significantly higher than for the control condition. These results

347 are reported in detail in Table 3.

348 The ROI analysis revealed that the right occipitoparietal region nearly showed a consistent

349 significant oddball response, left occipotoparietal region showed a significant oddball

350 response when there was a relatively high level of oddball repetition and the central/vertex

351 region only showed a significant oddball response to the very high repetition condition.

352 Whether the lack of a significant oddball response in conditions with lower/no repetition (e.g.,

353 C3 and C4) was due to distinct neural sources for repetition and recognition, or a result of

354 poor signal strength remains unclear.

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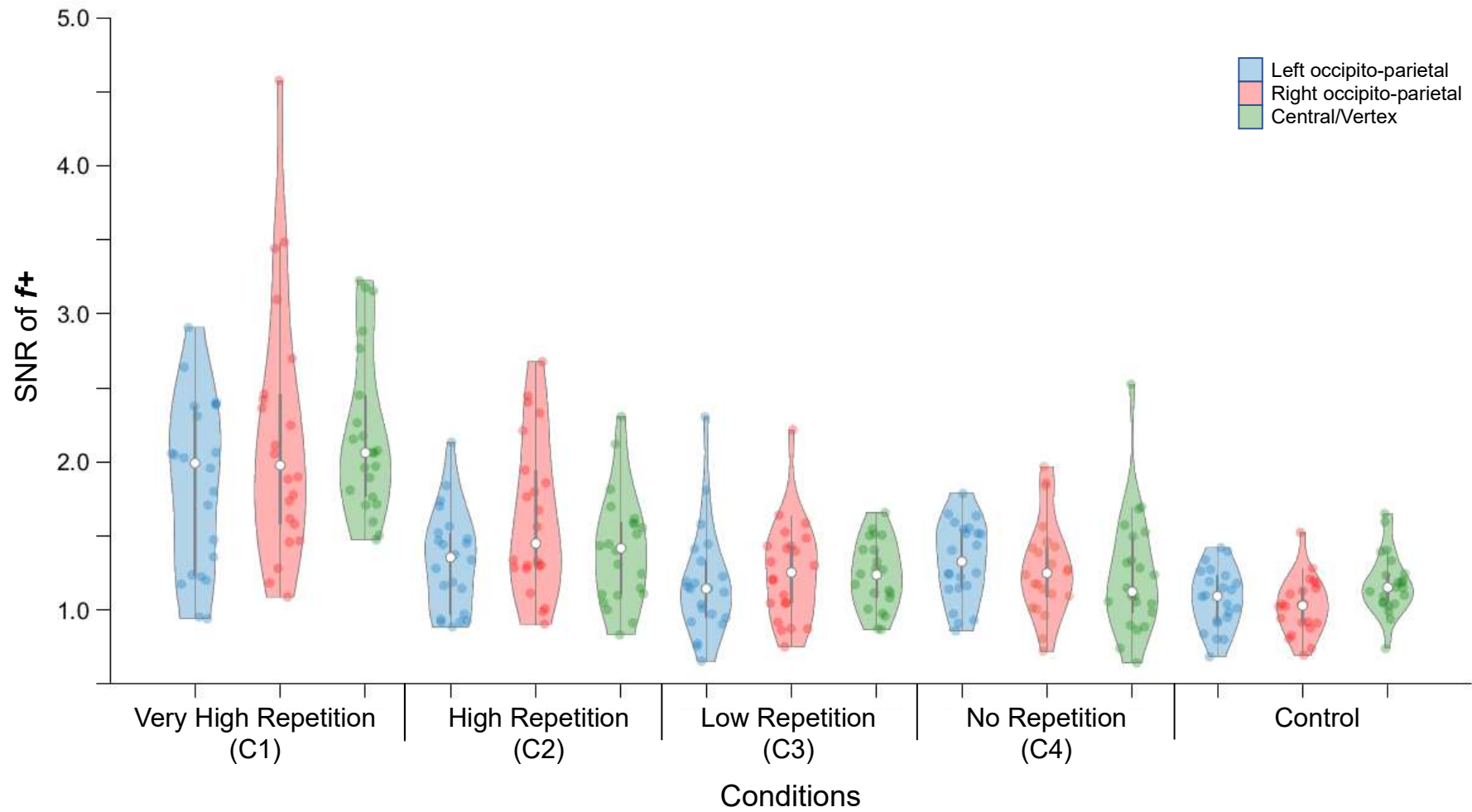
Figure 4: Violin plots of *f+* calculated for each condition and ROI. Tukey boxplots reflect the median and inter-quartile ranges, width of the violin

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

a) Main Effects	df	F	p	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 *f+*	95% CI	p	η_p^2
Very high repetition (C1)	0.97	0.74, 1.21	**<.001**	**.781**
High repetition (C2)	0.36	0.21, 0.52	**<.001**	**.536**
Low repetition (C3)	0.13	0.04, 0.23	**.009**	**.285**
No repetition (C4)	0.19	0.05, 0.32	**.008**	**.289**

358 **c) Post-hoc analyses of ROI x Condition interaction**

	Very high repetition (C1) vs Control			High repetition (C2) vs Control			Low repetition (C3) vs Control			No repetition (C4) vs Control		
	Mean difference *f+* (95%CI)	p	Cohen's d	Mean difference *f+* (95%CI)	p	Cohen's d	Mean difference *f+* (95%CI)	p	Cohen's d	Mean difference *f+* (95%CI)	p	Cohen's d
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

359 **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
360 oddball f+ responses. **b)** Pairwise comparisons of the effect of Condition alone on oddball f+ responses. Values in bold indicate significant differences after
361 Bonferroni correction of .05/4= .013. **c)** Post-hoc pairwise comparisons of the ROI x Condition interaction. Values in bold indicate significant differences after
362 Bonferroni correction (.05/12= .004). Cohen's d was calculated using the effect size estimates in the repeated measures designs tool developed by (Lenhard
363 & 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. The underlying behavioural measures that give rise to the d prime measure, such as hit rate and false alarm rate, are reported in Supplementary Table 2. 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.
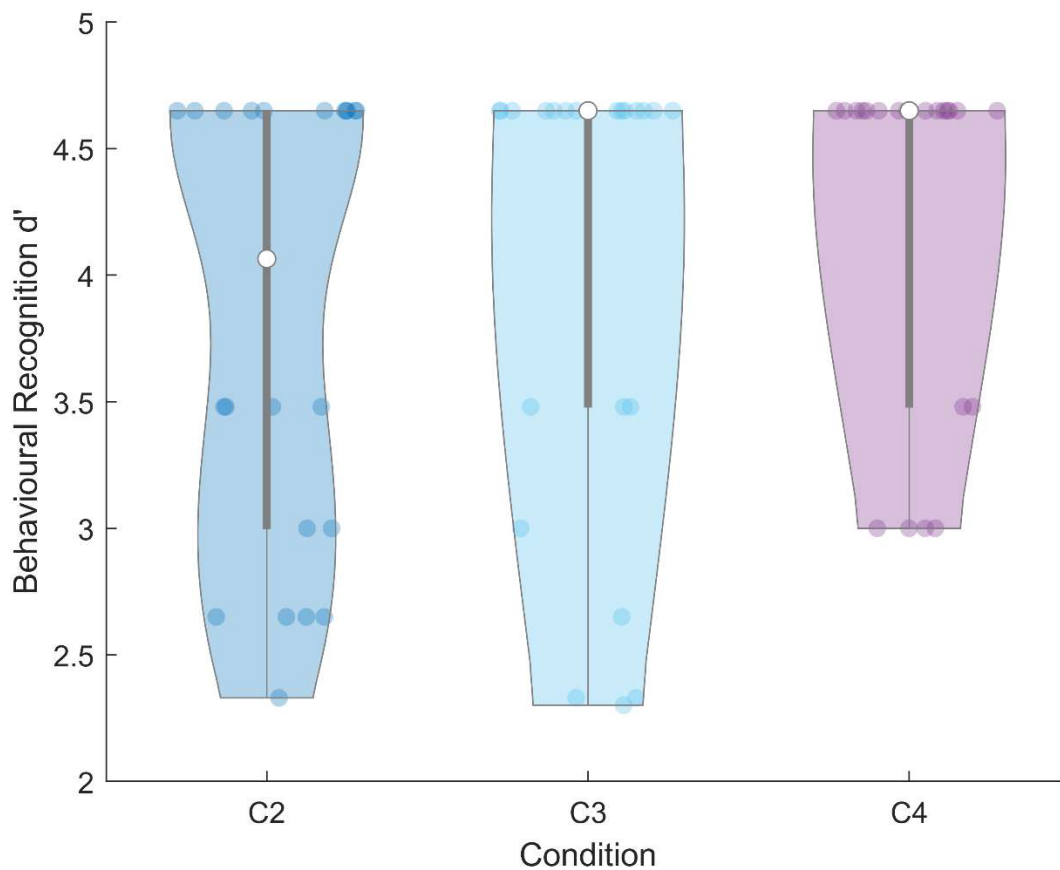
376 **Figure 5:** Violin plots demonstrating the behavioural recognition memory (Yes/No) task d'

377 scores for the conditions with 8 or more oddball images (C2-C4). Tukey boxplots reflect the

378 median and inter-quartile ranges, whereas width of the violin plots reflects kernel density

379 estimated using MATLAB's ksdensity function.

380

381 The difference in oddball object recognition was analysed using the Friedman test, which

382 revealed a statistically significant difference between the mean ranks of d' between conditions

383 C2, C3 and C4, $\chi^2(2) = 7.302$, $p = .026$. However, post-hoc pairwise comparisons showed no

384 significant differences between individual conditions (C2-C3 $p =.874$; C2-C4 $p =.179$; C3-C4

385 $p=1.000$).

386

387 **3.4   Wechsler Memory Scale – IV performance**

388 Z Scores were calculated from Scaled Scores for the purpose of visualising performance

389 across tasks (see Figure 6).

390
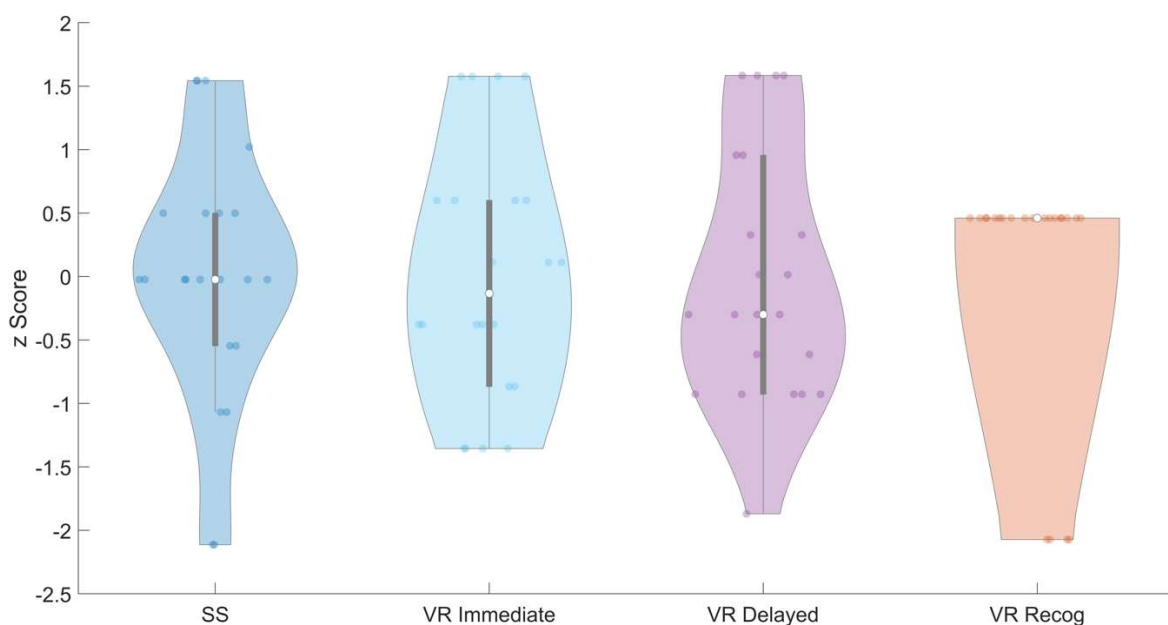
Figure 6: Violin plots illustrating the z scores of participants' performance on the four WMS-IV tasks. SS: Symbol Span, VR Immediate: Visual Reproduction Immediate Recall, VR Delayed: Visual Reproduction Delayed Recall, VR Recog: Visual Reproduction Recognition.

Participants' mean (±SD) subtest scaled scores were: SS = 10 ±1.91, VRI = 10.77 ±2.0 and VRII = 11.95 ±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 no repetition condition (C4) (SS: r = -.043, p = .425; VRI: r = -.264, p = .118; VRII: r = -.133, p = .277), low repetition 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 no repetition condition (C4) (r = .078, p = .730) and low repetition 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). The p-values were not corrected for multiple comparisons. However, since there were three comparisons made (f+ SNR vs d' for C2, C3 and C4, e.g., C2 f+ SNR vs C2 d'), we accept p<0.0167 (p=0.05/3 = 0.0167) as statistically significant. Therefore, *p*=0.010 remains statistically significant even with the lowered Bonferroni-corrected threshold.

4   Discussion

4.1   Summary of key findings

This study investigated whether the extent to which the FPVS response to previously seen and encoded oddball stimuli reflects recognition or repetition priming by manipulating the degree of repetition of the oddball stimuli from very high 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 very high repetition (C1), high repetition (C2) and no repetition (C4) conditions, however no significant oddball response was observed in the low repetition (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 very high repetition condition and absent in the no repetition 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 very high repetition condition.

444   Overall, the findings extend our understanding of the effect of repetition in FPVS recognition

445   memory oddball responses by showing that while repetition priming plays a significant role in

446   enhancing the oddball response, it is not the sole driver of the response, as oddball responses

447   were observed in the complete absence of repetition priming (in C4).

448

449   **4.2   Very high repetition vs no repetition signals**

450   The effect of oddball image repetition (priming) was prominent in the scalp averaged

451   recognition memory response. One of the critical questions remaining from Stothart et al.

452   (2020) was whether recognition memory could be measured using FPVS in the absence of

453   repetition priming, our findings confirm this is possible. FPVS measures of implicit recognition

454   memory therefore contain, as a minimum, a measure of the unconscious and automatic

455   process that underlies familiarity.

456   The very high repetition condition (C1) evoked the strongest oddball signal compared to the

457   other conditions with lower levels of oddball repetition. A number of factors may result in this

458   augmentation of the oddball response. A possible explanation, stemming from single-system

459   theory, is that repetition priming strengthens the memory of the image learned in the encoding

460   phase (Park & Donaldson, 2016). This happens through repeated exposure to oddball images

461   that leads to an increase in the strength of the memory signal driving recognition and priming

462   (Berry et al., 2012). It is also likely that as oddball stimuli are repeatedly presented they are

463   consciously, explicitly recognised. As responses are quantified in the frequency domain, it is

464   not possible in conditions with high levels of repetition to delineate the implicit and explicit

465   elements of the response. However, the current study demonstrates that it is possible to

466   manipulate their contribution to the response, and that a purely implicit response is detectable.

467   This gives flexibility to the approach, with the balance of implicit and explicit responses being

468   a parameter to adjust when addressing future research questions.

469   Another possible driver of the repetition response could be statistical learning (Mandikal

470   Vasuki, Sharma, Ibrahim, & Arciuli, 2017; Romberg & Saffran, 2010). For example, during the

471   task participants may categorise stimuli into "repeating" and "non-repeating" classes or,

472   alternatively, they could realise that four non-repeating images are followed by a fifth repeating

473   image, also known as "chunking" (Dehaene, Meyniel, Wacongne, Wang, & Pallier, 2015). This

474   online classification of oddball stimuli would result in predictive feedback and the classic visual

475   mismatch response to oddball stimuli (Näätänen & Michie, 1979; Stefanics, Astikainen, &

476   Czigler, 2014).

477

478   **4.3   EEG recognition, behavioural recognition and WMS-IV visual memory**

479   **responses**

480   Behavioural recognition measures showed that participants had encoded oddball images

481   successfully, as their post-FPVS behavioural recognition scores were near ceiling.

482   Participants' WMS-IV scores were within normal ranges established in previous normative

483   samples (Wechsler, 2009). However, there were also no correlations with performance on

484   the visual memory subtests of the WMS-IV, suggesting the WMS-IV tasks and the FPVS task

485   might be measuring different cognitive processes. Participants' implicit recognition memory,

486   as a proxy of their oddball response measured by FPVS, was not correlated with the post-

487   FPVS behavioural recognition measures in conditions with low repetition or no repetition (C3

488   and C4), though there was a significant correlation between the EEG measure and

489   behavioural measure of the high repetition (C2) condition. However, future studies should

490   further probe the relationship between *f+* and conscious recognition with more demanding

491   behavioural tasks that avoid ceiling effects. Additionally, FPVS oddball response is a neural

492   proxy measure of memory, potentially reflecting the early, automatic stages of recognition.

493   Therefore, it is important to highlight that FPVS oddball responses are not a direct measure

494   of cognition, but a proxy of a composite of cognitive processes underlying recognition memory.

495

4.4 Clinical applications

496

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.

518

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 very high repetition and no repetition 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 and 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,

545 the next steps should be to identify the neural sources of the FPVS recognition memory signal,

546 which would contribute to the debate regarding single versus multiple memory systems, and

547 for clinical neuroscientists, the next steps should be to investigate the predictive utility of the

548 FPVS recognition memory test as an early detection tool for neurological conditions

549 associated with recognition memory impairment (e.g. Alzheimer's Disease).

550

551 **Acknowledgements**

Supplementary Information

Supplementary table 1: z score values of group and scalp average of SNR per condition for

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

Supplementary table 2: The first 22 rows of this table state each participant's Hit Rate, False Alarm Rate (FA Rate), Corrected Hit Rate (Hit Rate – False Alarm Rate) and d' for each condition where a behavioural recognition task was completed. The final row at the bottom states the average of each metric across 22 participants.

C2 Hit Rate	C2 FA Rate	C2 Corr Hit Rate	C2 d'	C3 Hit Rate	C3 FA Rate	C3 Corr Hit Rate	C3 d'	C4 Hit Rate	C4 FA Rate	C4 Corr Hit Rate	C4 d'
1	0.38	0.63	2.65	1	0	1	4.65	1	0.25	0.75	3
1	0	1	4.65	1	0.5	0.5	2.33	1	0	1	4.65
1	0	1	4.65	1	0	1	4.65	1	0	1	4.65
1	0	1	4.65	1	0	1	4.65	0.88	0	0.88	4.65
1	0.5	0.5	2.33	1	0.13	0.88	3.48	1	0	1	4.65
1	0.38	0.63	2.65	1	0.5	0.5	2.33	1	0.25	0.75	3
1	0	1	4.65	1	0	1	4.65	1	0	1	4.65
1	0.13	0.88	3.48	1	0.13	0.88	3.48	1	0	1	4.65
1	0.38	0.63	2.65	1	0.13	0.88	3.48	1	0.25	0.75	3
1	0	1	4.65	1	0	1	4.65	1	0	1	4.65
1	0.13	0.88	3.48	1	0	1	4.65	1	0	1	4.65
1	0.25	0.75	3	1	0.25	0.75	3	1	0.25	0.75	3
0.88	0	0.88	3.48	1	0	1	4.65	1	0	1	4.65
1	0	1	4.65	0.88	0.13	0.75	2.30	0.88	0	0.88	4.65
1	0	1	4.65	1	0	1	4.65	1	0	1	4.65
0.88	0	0.88	3.48	1	0	1	4.65	1	0	1	4.65
1	0	1	4.65	1	0	1	4.65	0.88	0	0.88	4.65
1	0	1	4.65	1	0	1	4.65	1	0	1	4.65
1	0.25	0.75	3	1	0	1	4.65	1	0	1	4.65
1	0	1	4.65	1	0	1	4.65	0.75	0	0.75	4.65
1	0.38	0.63	2.65	1	0.38	0.63	2.65	1	0.13	0.88	3.48
1	0	1	4.65	1	0	1	4.65	1	0.13	0.88	3.48
0.99	**0.13**	**0.86**	**3.82**	**0.99**	**0.10**	**0.90**	**4.01**	**0.97**	**0.06**	**0.91**	**4.24**

<div style="text-align: center;">**References**</div>

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