Vision Research 110 (2015) 1–6

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Principal component analysis of the memory load effect in a change detection task

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ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form 11 January 2015
Available online 10 March 2015

Keywords:
P3
PCA
Change detection task
Visual working memory
Event-related potentials

ABSTRACT

Previous research using the change detection task has found little or no relationship between P3 amplitude and working memory load. This contrasts with findings from other paradigms that indicate a decrease in P3 amplitude with increases in working memory load. We adopted a principal component analysis strategy to resolve this discrepancy. After ERPs were decomposed, the P3 component decreased in amplitude when the memory load increased. Its amplitude was also associated with individuals' working memory capacity. In conclusion, P3 plays a critical role in change detection task as it does in other working memory tasks.

1. Introduction

Working memory (WM) is a system that temporarily maintains information active and keeps it available for further operations (Ricker, AuBuchon, & Cowan, 2010). In the visual domain, an important feature is its severely limited capacity (Cowan, 2001; Luck & Vogel, 1997; Rouder et al., 2008). To measure visual WM (VWM) capacity, the change detection (match-to-sample) task has been widely used in behavioral and neurological studies (e.g. Cowan, 2001; Cowan et al., 2005; Vogel & Machizawa, 2004). A principle virtue of this task is that VWM capacity can be estimated as a single number by formulas first proposed by Pashler (1988), and later modified by Cowan et al. (2005). Most recently, Vogel and colleagues adapted the task to isolate the maintenance process itself using bilateral displays with unilateral cuing while measuring event-related potentials from EEG (Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005). They found a direct correlation between VWM capacity estimates and contralateral delay activity (CDA). Besides the CDA, another ERP component, the negative slow wave (NSW) has been observed across VWM studies by using the change detection task as well (Ruchkin et al., 1992). Ruchkin et al. (1992) observed this negative wave during the maintenance period, and found that its amplitude increased as a function of memory load.

Unlike CDA or NSW, ERP component P3 elicited in change detection task has been reported to be unrelated to memory load (Ruchkin et al., 1992). This finding was inconsistent with other working memory studies using different paradigms (Kok, 2001; Polich, 2007; for review). In those paradigms, P3 amplitude typically decreases as memory load increases. For example, McEvoy, Smith, and Gevins (1998) used an *N*-back task and found P3 amplitudes elicited by the target reduced when memory load increased from 1 to 3. In addition to increasing memory load, increasing the complexity of conceptual operations also reduces P3 amplitude. For example, using rotated letters in Sternberg (1966) memory scanning task, Wijers et al. (1989) found that adding a mental rotation operation to the items maintained in working memory reduced the P3 at the posterior sites. They suggested the P3 reduction effect was due to an overlap between P3 and a sustained negative wave which had a similar onset latency (300 ms poststimulus as P3). But later, Mecklinger et al. (1992) using a memory search task employed principal component analysis (PCA) to dissociate the P3 from the NSW and found that the attenuation of P3 with memory load increases was due to changes in both P3 and NSW. The PCA results indicated that the component identified as P3 decreased, and the one for NSW increased as a function of memory load. They were both sensitive to memory load, but in a reciprocal fashion.

The observation that the amplitude of P3 reduces with increased memory load in other paradigms taxing working memory, together with the analysis of Mecklinger et al. (1992) suggests that maybe the overlap between P3 and other components was the reason that P3 elicited by the change detection task was not sensitive to memory load in the Ruchkin et al. (1992), because those two subcomponents may be reciprocally related to memory load

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http://dx.doi.org/10.1016/j.visres.2015.01.028
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during the P3 latency. In the current study, we applied PCA to ERP waveforms in the change detection task in order to separate the possible subcomponents influencing P3 amplitude. We ask whether memory load influences the score of PCA derived P3-like component in a change detection task in a manner similar to other WM tasks. That is, would the score of P3-like component decrease with increases in memory set size when other possible components are separated from it using PCA?

2. Materials and methods

2.1. Participants

Twenty-seven college students (11 male and 16 female) with mean age 20.15 (*SD* = 0.5) gave informed consent to participate this study in return for course credit. The study was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and has been approved by the Institutional Review Board of Miami University. All participants had normal or corrected-to normal vision, and reported normal neurological and psychiatric health.

2.2. Stimuli and procedure

The version of the change detection task we used was taken after Cowan et al. (2005). Stimuli were arrays of colored squares each subtending $0.75^\circ \times 0.75^\circ$ visual angle and randomly distributed within $9.8^\circ \times 7.3^\circ$ rectangular gray regions. The square colors were selected randomly from a set of seven highly discriminable colors (red, blue, violet, green, yellow, black, and white), and no color could appear more than twice in an array.

On each trial, a fixation cross appeared for a random time ranging from 300 ms to 400 ms, followed by the memory array of colored squares whose duration was 100 ms. A 900 ms gray screen replaced the memory array. The test array then appeared for as long as 3 s or until the participants' response whichever came first. In the test array, all the squares were same as those in the memory array except that one of them was randomly chosen and cued by black outline with 1° of visual angle. Its color was either replaced by one of the other colors or stayed the same. On half of the trials, the cued square in the test array changed, on the other half it remained the same. This was randomly determined across trials. The participants' task was to indicate whether the color in the cued square had changed from that of the memory array. Thirty practice trials occurred at the beginning of experiment. Following that were two blocks of 600 trials each, including equal number of trials with 4, 6, and 8 squares per array in random order.

2.3. EEG recording and analysis

Electroencephalographic (EEG) activity was recorded from 32 electrode sites at 250 Hz using an Electrical Geodesics (Eugene, OR) system. All channels were referenced to the vertex (Cz) during data acquisition, and their impedances were adjusted below 50 KΩ. After 0.1 Hz high pass filter, data were imported to EEGLab toolbox for analysis (Delorme & Makeig, 2004). High-frequency muscle noise and other irregular artifacts were identified by visual inspection and removed. After running ICA, the non-brain artifacts components (e.g. eye blink, eye movement, muscle or line noise) were removed (Makeig & Onton, 2013). The reconstructed data were 45 Hz low-pass filtered and re-referenced offline to the average of left and right mastoids. Correctly responded trials were used for further analysis.

ERPs time-locked to the memory array onset were segmented from 100 ms prior to the memory array until 1000 ms after the memory array onset ending the epoch before test array onset. Single participant's epochs were averaged into ERPs for each channel and each set size. The averaged ERPs were aligned to a 100 ms pre-stimulus baseline. The traditional ERP component P3 amplitudes were measured by computing the average amplitude over its latency range. The latency ranges used were 400–600 ms for Fz, and 300–500 ms for Cz and Pz.

To obtain variables for Principal Components Analysis (PCA), all participants' averaged ERP were down sampled to 125 Hz, with time window (0–1000 ms). Twenty-two electrodes were included for PCA. They were Fp1, Fpz, Fp2, F3, Fz, F4, F7, F8, Fcz, T3, C3, Cz, C4, T4, T5, T6, P3, P4, Pz, O1, Oz, and O2. The data matrix for PCA consisted of 125 columns (variables), and 1782 observations (27 participants × 3 set sizes × 22 electrodes). The data were submitted to R and the Psych Package was used to perform PCA on the covariance matrix, and then promax rotated (Dien, Beal, & Berg, 2005; Kayser & Tenke, 2003; Mecklinger et al., 1992).

3. Results

3.1. Behavioral results

Repeated measures ANOVA with the factor set size (4, 6, and 8) was applied to response times. Significant effects of set size were examined further using post hoc tests. Greenhouse-Geisser corrections were applied to obtain appropriate degrees of freedom when the assumption of sphericity was violated.

As can be seen in Table 1, response time increases as a function of set size, $F(1.4, 37.5) = 66.14$, $p < .001$, $\eta^2 = 1$. As a measure of WM capacity, each participant's Cowan' *k* within each set size was computed based on hit and false alarm rate (Cowan et al., 2005). Averaged values were obtained across set size to represent *k*, which ranged from 1.35 to 4.88, with mean of 3.22. Thus, on average, WM capacity in this task was around three as in similar studies (Cowan, 2001; Vogel & Machizawa, 2004).

3.2. ERP results

Fig. 1 presents the grand average ERPs for each set size at central midline electrodes Fz, Cz, and Pz. Though Fig. 1 suggests P3 amplitude changes as a function of set size, this main effect was not significant, $F(2, 52) = 2.43$, $p = .10$. There was no significant electrode main effect, $F(1.5, 39.1) = 1.26$, $p = .29$, or the electrode × set size interaction, $F(1.9, 50.0) = 1.07$, $p = .35$.

3.3. PCA results

After PCA was performed on the covariance matrix, the promax rotated component loadings for four components were extracted from the PCA. An examination of the scree plot (Fig. 2) of eigenvalues vs. number of components in the PCA suggested that five were sufficient to represent the ERPs (Johnson & Wichern, 2007). We present the first four in Fig. 3 as they are sufficient to interpret the main findings. These components accounted for 83% of the variance in the data set. Component 1 and component 4 were excluded for further analysis because they were not sensitive to memory load.

Table 1
Mean (SD) RT and Cowan's *k* as function of set size.

	Size 4	Size 6	Size 8
RT(ms)	723(114)	778(127)	805(130)
Cowan's *k*	3.07(0.56)	3.23(0.97)	3.37(1.18)