

Frontal steady-state potential changes predict long-term recognition memory performance

Richard B. Silberstein*, Philip G. Harris, Geoffrey A. Nield,
Andrew Pipingas

Brain Sciences Institute, Swinburne University of Technology, P.O. Box 218 Hawthorn, Victoria 3122, Australia

Received 11 January 2000; received in revised form 28 April 2000; accepted 5 May 2000

Abstract

Converging evidence from event-related potential and functional brain imaging studies suggests that the brain activity at posterior regions of the frontal cortex can predict the strength of long-term memory traces. This study examined the relationship between posterior frontal steady-state visually evoked potential (SSVEP) latency changes and recognition memory after a delay of 7 days. Thirty-five female subjects viewed an 18-min television documentary program interspersed with 12 unfamiliar television advertisements while brain electrical activity was recorded from four pre-frontal, two posterior frontal and two occipital scalp sites. After 7 days, the recognition memory was tested for images coinciding with the 20 most prominent frontal SSVEP latency minima and maxima during the viewing of ten contiguous advertisements (advertisements 2–11). We found that images coinciding with posterior frontal latency minima were more likely to be recognized (58.7% recognition) than images coinciding with SSVEP latency maxima (45.3% recognition). Furthermore, the relationship between posterior frontal SSVEP latency and recognition performance after 7 days was only apparent at the left posterior frontal site. The correlation between the recognition performance and SSVEP latency evaluated at all eight sites reached significance only at the left posterior frontal site. These findings suggest that frontal SSVEP latency variations can be used to assess the strength of long-term memory encoding for naturalistic stimuli. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Recognition memory; Long-term memory; Steady-state visually evoked potential (SSVEP); Pre-frontal cortex; Steady-state probe topography (SSPT)

* Corresponding author. Tel.: +61-3-9214-8273; fax: +61-3-9214-5525.
E-mail address: rsilberstein@bsi.swin.edu.au (R.B. Silberstein).

1. Introduction

Converging evidence from event-related potential and functional brain imaging studies suggests that cortical activity at posterior regions of the frontal cortex and pre-frontal cortex predicts the strength of long-term memory traces (Rugg, 1996; Brewer et al., 1998; Buckner et al., 1999). Visually presented material that is subsequently recalled is associated with increased activity at a number of frontal and pre-frontal cortical sites, including the dorsal part of the inferior frontal cortex (near Brodmann's areas 6 and 44) and the ventral pre-frontal cortex near Brodmann's areas 45, 46 and 47 (Buckner et al., 1999). The nature of the material being encoded into memory also influences the laterality of activation. Encoding verbal material has been associated with left frontal activation while encoding non-verbal material, such as unfamiliar faces, has been associated with right frontal activation (Kelley et al., 1998).

While positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies have yielded important insights into the brain activity correlates of memory encoding, these methodologies do not possess the temporal resolution necessary to investigate the rapid changes in brain activity associated with extended cognitive tasks, such as the memory encoding of continuously presented material, e.g. film.

Previous work by Silberstein suggests that steady-state probe topography (SSPT), a methodology that utilizes the steady-state visually evoked potential (SSVEP), offers the opportunity of a high temporal resolution analysis of brain electrical correlates of extended tasks coupled with noise resistance (Regan 1989; Silberstein, 1995). We have reported strong cognitive task effects on the SSVEP, when the eliciting stimulus comprises a uniform visual flicker superimposed on the computer monitor used to present the cognitive task (Silberstein et al., 1990; Silberstein, 1995). Analyzing the SSVEP from 64 scalp sites indicated that increased visual vigilance was associated with an occipito/parietal and centro/parietal reduction in the magnitude of the SSVEP elicited by the irrelevant visual flicker. Findings yielded by this technique appeared analogous to the regional

reductions in alpha activity associated with a cognitive task (Pfurtscheller and Klimesch, 1990). The availability of an external reference signal in the stimulus also permits an estimation of changes in SSVEP latency (Line et al., 1998; Silberstein et al., 1998).

We have previously suggested that such SSVEP latency changes may index variations in neural information processing speed, and such variations are a reflection of excitatory and inhibitory processes. This interpretation is supported by a number of findings. Specifically, faster responses in a visual vigilance task were associated with larger prefrontal SSVEP latency reduction (Silberstein et al., 1996). A recent study of the SSVEP latency changes in ADHD reinforced this interpretation. Normal controls demonstrated transient prefrontal SSVEP latency reductions following the appearance of a target stimulus, while subjects diagnosed with ADHD showed no such latency reduction. We speculated that the failure to exhibit transient SSVEP latency reductions in ADHD might be a consequence of inadequate excitation of prefrontal networks at specific times in the AX sequence (Silberstein et al., 1998). In an auditory pattern recognition task, subjects that performed better demonstrated sustained SSVEP latency reductions over the left frontal areas during the pattern retention phase of the task (Harris and Silberstein, 1999)

In this study, we examined the relationship between pre-frontal SSVEP latency changes and the strength of memory encoding of naturalistic audio-visual material presented on a television monitor. We hypothesized that the images associated with increased frontal excitation as indicated by a reduction in SSVEP latency would be remembered better than images associated with reduced frontal activation.

2. Methods

Thirty-five female subjects with normal vision aged 25–45 years (mean = 37.6 years; S.D. = 3.6 years) participated in the study. Participants attended two experimental sessions spaced 7 days apart. In the first session, brain electrical activity

was recorded while participants viewed an 18-min television documentary interspersed with 12 30-s US television advertisements. The first and last advertisement (nos 1 and 12) occurred prior to the start of the documentary and at the end of the documentary. The remaining 10 advertisements were presented in two blocks of five advertisements that commenced 4 min and 10 min into the documentary. The two advertisement blocks were counterbalanced to reduce order effects. While none of the advertisements had been broadcast in Australia, all of the products advertised were available locally. The participants were informed that in a subsequent session they would be viewing slides and answering questions, although no explicit indication was given that recognition of the advertisements would be tested.

Seven days after the initial recording, the participants performed a recognition memory task where they viewed a random array of the 40 advertising frames selected from advertisements 2–11, and 40 novel images also taken from unfamiliar television advertisements. The first and last of the 12 advertisements were not used so as to avoid primacy and recency effects. The procedure employed to select the frames is described below. Participants indicated, via a two-button response box (yes, no), whether an image was recognized from the previous recording session. The timing of the image presentation was subject-paced, with a maximum 5-s presentation and a 1-s delay separating the presentation of each image.

3. Stimulus

The stimulus used to evoke the SSVEP was a white 13-Hz sinusoidal flicker subtending a horizontal angle of 160° and a vertical angle of 90°. The modulation depth of the stimulus when viewed against the background was 45%. A set of goggles that permitted the sinusoidal flicker to be superimposed on the viewing field was used to present the stimulus (Silberstein et al., 1990).

Brain electrical activity was recorded from the left and right frontal sites situated over the cortical regions that were thought to participate in the establishment of long memory traces, i.e. between

C3 and F7 on the left hemisphere (C3–F7) and the corresponding locations on the right side (between C4 and F8) (C4–F8) (Buckner et al., 1999). We also recorded activity from six other sites. These were located half way between Fp1 and F7 (Fp1–F7), and halfway between Fp2 and F8 (Fp2–F8), and the following standard sites: F3, F4 and O1 and O2. The average potential of both earlobes served as a reference, and a nose electrode served as a ground. The brain electrical activity was amplified and bandpass filtered (3 dB down at 0.1 Hz and 80 Hz) prior to digitization to 14-bit accuracy at a rate of 250 Hz.

The major features of the signal processing have already been described (Silberstein, 1995). Briefly, the SSVEP was determined from the 13-Hz Fourier coefficients evaluated over 33 stimulus cycles, yielding a temporal resolution of approximately 2.5 s. The 33-cycle evaluation period was shifted by one stimulus cycle, and the coefficients were recalculated for this overlapping period. This process was continued until the entire 1080 s of activity was analyzed. An identical procedure was applied to data recorded from all eight recording sites. The smoothed Fourier coefficients were pooled across all subjects, the data transformed to polar form (magnitude and phase), and the changes in phase expressed as changes in latency.

4. Selection of material for testing

Pooled SSVEP latency minima for C3–F7 and C4–F8 were ranked in order of size and the occurrence time of the 20 most prominent minima from both sides were identified. A similar procedure was conducted for SSVEP latency maxima.

Nineteen maxima and minima were elicited over C3–F7 (8 minima and 11 maxima), whereas 21 were obtained over C4–F8 (12 minima and 9 maxima). Images coinciding with each of the 40 latency maxima and minima were extracted as single frames from the advertising material for subsequent memory recognition testing. Frames that featured explicit product branding were removed from the analysis and replaced with a frame coinciding with the next-ranking latency

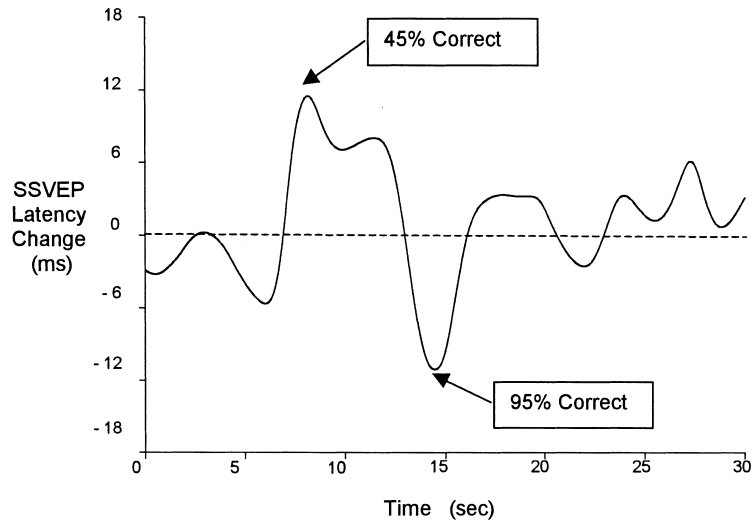


Fig. 1. Pooled SSVEP latency variations at the left frontal site (C3-F7) during one of the 30-s television advertisement. Subsequent recognition performance of slides extracted from the advertisement coinciding with latency maxima and minima are indicated on the figure. The horizontal line represents the mean SSVEP latency of all commercials viewed.

change. Frames from each of the ten commercials featured in both maxima and minima conditions.

5. Results

Performance on the recognition task varied widely between individuals. The best performer recognized 77.5% of the frames, while the lowest performance level was well below chance (50%) at 17.5%. Overall 52.8% of the frames were correctly recognized, which is not significantly different from chance performance. Subjects also correctly identified 79.8% of the frames, which were not previously seen, as novel.

Recognition performance was influenced by whether the frame coincided with an SSVEP minima or maxima at C3–F7 and C4–F8. Frames coinciding with latency minima were correctly recognized (58.7% of presentations) while frames coinciding with SSVEP latency maxima were correctly recognized (45.3% of presentations). A paired *t*-test examining differences in correct recognition of frames coinciding with latency maxima and minima was found to be highly significant ($t = 4.87$; *d.f.* = 34; $P = 2.5 \times 10^{-5}$, one-tailed).

These results strongly suggested that the successful encoding of the commercial material in long-term memory was associated with reductions in SSVEP latency at these frontal sites. Fig. 1 illustrates the variations in SSVEP latency at C3–F7 during a 30-s advertisement.

In order to examine hemispheric laterality effects, recognition performance was examined separately for the left (C3–F7) and right (C4–F8) electrodes. Fig. 2 illustrates the memory performance for frames coinciding with SSVEP latency maxima and minima at these sites.

Frames coinciding with left C3–F7 SSVEP la-

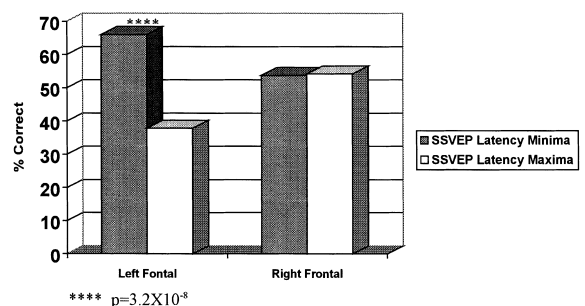


Fig. 2. Seven-day recognition memory performance for advertising images coinciding with left and right posterior frontal SSVEP latency minima and maxima.

tency minima were recognized in 66.0% (S.D. = 23.4%) of presentations, while frames coinciding with left C3–F7 SSVEP latency maxima were recognized on 37.9% (S.D. = 16.4%) of presentation. Recognition differences associated with SSVEP minima and maxima were highly significant ($t = 7.11$; d.f. = 34; $P = 3.2 \times 10^{-8}$, one-tailed).

Frames coinciding with right C4–F8 SSVEP latency minima and maxima were correctly recognized in 53.8% (S.D. = 21.6) and 54.2% (S.D. = 12.3%) of presentations, respectively, and were determined in a paired t -test to not be significantly different ($t = 0.17$; d.f. = 34; $P = 0.86$, one-tailed). Thus, our data suggested that the left C3–F7 site provided the principal contribution to the observed recognition differences across these frontal sites.

To examine the recording site specificity of the relationship between recognition performance and SSVEP latency, we calculated the correlation coefficient between recognition performance for the 40 repeated images and SSVEP latency at all eight recording sites. Using $P < 0.005$ to correct for multiple comparisons, we found that the relationship between recognition memory performance and SSVEP latency was significant only at the left frontal site C3–F7 (see Table 1)

6. Discussion

The group performance on the recognition task (52.9%) was not significantly different from chance levels. We suggested two factors that may

have contributed to this low overall performance level. Firstly, the combination of a single exposure to the advertisements and the 7-day interval between the exposure and recognition testing may have made recognition difficult. Another factor contributing to the low performance may have been a conservative decision-making strategy adopted by the participants. If participants indicated recognition only when they were confident of their choice, frames recognized with less confidence would have been signaled as not recognized or novel. The plausibility of this factor contributing to the low recognition rate is supported by the fact that, while subjects were only able to recognize 52.9% of the frames taken from the advertisements viewed previously, they were able to correctly identify 79.8% of the novel slides as novel.

While the overall recognition performance was low, our hypothesis that images associated with increased activity, as indicated by reduced SSVEP latency at C3–F7 and C4–F8, would be better recognized was confirmed. Images selected to coincide with SSVEP latency minima were significantly more likely to be recognized (58.7%) than those coinciding with latency maxima (45.3%).

Our results indicated that the relationship between SSVEP latency and recognition performance appears to be restricted to the left hemisphere site C3–F7. Our findings thus suggested a preferential role for the left hemisphere in determining the strength of long-term memory encoding for the type of audio–visual material used in this study. While the probability of recall varied from 66% for C3–F7 SSVEP latency minima to 37.9% for latency maxima, the right hemisphere SSVEP latency was apparently unrelated to probability of recall. We had not expected such a strong left hemisphere bias and, given the prominence of visual imagery in the material used, we had, in fact, expected a right hemisphere bias.

While we could not confidently identify the cause of the left hemisphere bias, we speculate that one or more of the following factors may have contributed. Firstly, the results may have been a consequence of the preferential role of the left hemisphere in the coding of both verbal and non-verbal memories. This is consistent with

Table 1
Correlation between SSVEP latency, and recognition memory performance

Left recording sites	Correlation	Right recording sites	Correlation
Fp1-F7	0.363	Fp2-F8	0.178
C3-F7	0.448 ^a	C4-F8	0.218
F3	0.263	F4	0.348
O1	0.162	O2	0.008

^a $P < 0.005$ (d.f. = 39; $r = 0.392$).

the hemispheric encoding/retrieval asymmetry (HERA) model suggested by Tulving et al., (1994). In the HERA model, the left hemisphere is proposed to play a dominant role for encoding both verbal and non-verbal episodic memory traces, while the right hemisphere played a dominant role in the retrieval of all episodic memory traces (Klingberg and Roland, 1998; Tulving et al., 1994). Our findings would, therefore, be consistent with this model.

In addition, restricting our participant pool to females may have also contributed to the left hemisphere bias for encoding long-term memory traces. This is suggested by the results of brain imaging studies examining the encoding process of emotional memories. An FDG PET study by Cahill et al. (1996) examined the relationship between the free recall of emotional film clips and amygdaloid complex activity in a group of eight males. They reported that the glucose metabolic rate in the right amygdaloid complex while viewing emotional films was highly correlated with the number of film clips recalled 3 weeks after viewing. In contrast, an O15 PET study by Taylor et al. (1998) examining the effect of emotional content of static visual stimuli (slides) on brain activity found increased left amygdaloid complex activity when encoding emotional slides in a group of eight females. While caution must be exercised in interpreting the significance of these two studies, they suggest that gender may be an important variable in determining the laterality of amygdaloid activity in response to emotional stimuli, and that gender may also influence the hemispheric laterality of neural mechanisms participating in the encoding of emotional long-term memory. Our observation of a strong left hemisphere bias in the relationship between SSVEP latency and recognition may thus be a consequence of restricting our participant pool to females.

In summary, these findings suggest that the left frontal areas play a role in long-term memory encoding for naturalistic stimuli, and provide further support for previous proposals of frontal lobe involvement in long-term memory encoding. Furthermore, these findings support the utility of the SSPT methodology in assessing the strength

of long-term memory encoding for naturalistic stimuli.

Acknowledgements

This work was supported, in part, by a research grant from NeuroVu Research Pty. Ltd. The authors acknowledge the advice and assistance of Ms Omnia Holland and Dr Nicole Hightet of OmniCom Research.

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