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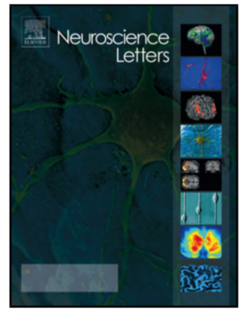

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What can ERPs tell us about the generation effect?

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Highlights

- Memory performance was better with generated than read words.
- Encoding-related ERP activity was greater under the generate than the read condition.
- This additional activity was correlated with an executive control index.

Abstract

The present experiment aimed to gain further understanding of the generation effect by investigating its neural correlates during encoding using event-related potentials (ERPs). Participants first encoded pairs of words under either a read or a generate condition and then completed a cued-recall task. Results confirmed the benefit of generation on memory performance. In addition, ERPs associated with the successfully encoded words had greater magnitude for generated than read words, from 900 to 1800 ms post-stimulus, on middle and bilateral frontal and parietal electrodes sites, mostly on the right hemisphere. Analyses also revealed that this greater activity was significantly correlated with executive control abilities but not with semantic knowledge. These findings show that generation is associated with greater later neural activity, suggesting the use of additional processes. Our findings also provide some evidence in support of the cognitive effort hypothesis of the generation effect.

Keywords: Memory, encoding, generation effect, ERPs

1. Introduction

Over the years, an important aim of research on memory has been to determine the conditions that can help improve memory performance. The generation effect is the phenomenon whereby an individual typically remembers more easily an item that has been produced by him/herself during encoding than one that has been externally presented [1]. In the classic paradigm, participants are asked to memorize a list of items under two conditions. Some of these to-be-remembered items are provided by the experimenter in their complete form (read condition; e.g. *LEAF-VEGETABLE*), while for the others, participants have to generate the target item from a semantically or phonologically related cue (generate condition; e.g. *LEAF-VEGET*__). The better performance when generating than reading has been demonstrated in a wide range of generation tasks, with different kinds of material, and their benefits have been proven in both healthy adults and neurological patients [see 2 for a review]. Several hypotheses have been suggested to explain the cognitive mechanisms involved in the generation effect. Some authors have argued that self-generated materials are remembered better because generation requires the use of processing resources and thus involves more effortful cognitive processes [3, 4, 5, 6]. For instance, Taconnat et al. [5] demonstrated that the generation effect of rhymes was related to an executive composite score, suggesting that this encoding strategy is strongly dependent on executive functioning abilities. Another explanation that has been put forward is based on the depth-of-processing model [7] and suggests that generating the target leads to deeper (i.e. semantic) processing and thus to a higher level of memory performance than simply encoding items passively. More precisely, some researchers have suggested that the generation effect may be due to the enhancement of lexical or semantic activation when the target item is self-generated [8].

Despite the abundance of research on the generation effect, there has been little focus on the neural mechanisms underlying the benefit of generation. To our knowledge, only two studies have directly explored the neural basis of the generation effect [9, 10]. Rosner et al. [9] compared fMRI activity when participants had to encode cue-target synonyms either by reading them (e.g. *GARBAGE-WASTE*) or by generating them from word-fragment cues (e.g. *GARBAGE-W_ST_).* Their memory for target words was then assessed using a recognition memory task including confidence ratings (high vs. low). Analyses revealed that encoding-related activity associated with subsequently remembered items (Hits) was greater under the generate than the read condition in a subset of regions. This included prefrontal (inferior frontal gyrus, middle frontal gyrus) and posterior regions (inferior temporal gyrus, lateral occipital cortex, parahippocampal gyrus, ventral parietal cortex). Comparison of activity elicited by items remembered with high confidence revealed a very similar network where activity was greater under the generate than the read condition. Correlational analyses showed that the magnitude of this read vs. generate difference was associated with the behavioral benefit of self-generation (better performance under the generate than the read condition). In another attempt to explore the neural circuits underlying the generation effect, Vannest et al. [10] asked participants to memorize the second word of word pairs related either phonologically (e.g. rhymes: *CARE-DARE*) or semantically (e.g. Antonyms: *HOT-COLD*) under a generate or a read condition, and then to complete a recognition task on the target items. As expected, memory performance was better for generated words than for words that were only read. fMRI data revealed a broad network of regions in which activity was greater under the generate than the read condition, including middle, medial and inferior frontal gyri, anterior cingulate, temporo-parieto-occipital regions and caudate nucleus. Other regions were activated more strongly for the read than the generate condition, such as the left medial and superior frontal cortex, bilateral insula, inferior parietal cortex and precuneus. In addition, a significant subsequent memory effect, with greater activity for subsequently remembered items than forgotten items, was observed only under the generation condition. These findings were interpreted as suggesting that self-generated information engages a wider network of regions because of a greater involvement of semantic properties. These findings seem to be in line with studies showing that deep encoding operations lead to greater fMRI activity than shallow operations in several areas of the frontal cortex, especially in the left inferior prefrontal cortex, in regions of the mediotemporal lobe, such as the left hippocampus, and posterior associative regions [11, 12, 13]. In addition, several regions have been found to be activated when generating words using a semantic (e.g. synonym generation) or a phonological rule (e.g. rhyme generation) [14, 15]. This “generation network”, which is more active when generating than reading words, involves not only left inferior frontal regions, but also regions of the temporal cortex and the striate/extrastriate cortex, which is consistent with the role of these structures in the generation effect, as described above [16].

Despite the excellent temporal resolution of event-related potentials (ERPs), which may provide relevant information about the neural correlates of the generation effect, no study has yet used this method with a generation paradigm. However, electrophysiological studies have revealed a pattern of neural activity associated with semantic processing, which can be assumed to be involved in the self-generation process. Most ERP studies investigating the neural correlates of encoding processes have used subsequent memory paradigms, generally showing greater activity for items that are subsequently remembered than for those that are not (SME: Subsequent memory effect) [for reviews, see 17, 18, 19], appearing from about 300 ms post-stimulus and lasting for several hundred milliseconds, widely distributed on the scalp. Studies manipulating the type of encoding task have mostly found that the SME is greater for tasks requiring a deep as opposed to a shallow level of processing. These encoding effects may also differ qualitatively, rather than only quantitatively. For instance, Otten et al. [13] found that an animacy task gave rise to a positive-going SME, whereas the SME observed in an alphabetic task had a negative polarity, suggesting task-specific neural systems. In several of these studies, ERP effects also had a more frontal distribution under deep than shallow conditions. Kuo, Liu, Ting, & Chan [20] interpreted this additional activity under deep conditions as reflecting the involvement of strategic processes mediated by executive functions.

The aim of this study was thus to gain further understanding of the cognitive and neural processes underlying the robust benefit of generation, using ERPs. More precisely, we explored ERP activity while participants were encoding pairs of words using a generation paradigm, before completing a cued-recall task. At a behavioral level, we expected to confirm the generation effect, with better memory performance under the generate than the read condition. We expected to observe at least quantitative differences between conditions, with greater activity for the generate than the read condition, appearing mostly in the latest periods, given that the generation process may take some time. We also conducted correlation analyses in order to define the mechanisms involved in the generation effect and more precisely, to disentangle the executive control and semantic hypotheses of the generation effect. If the generation effect is driven by greater semantic activation for generated words, we should observe a correlation between the generation effect and semantic measures. On the other hand, correlations between the generation effect and executive control measures would suggest that the generation effect is the consequence of a more efficient mobilization of controlled cognitive resources when generating a word.

2. Material and methods

Participants were 14 young adults. All were right-handed, native French speakers with normal or corrected-to-normal vision. The data of two participants could not be used because they elicited too few ERP trials under critical conditions. The mean age of the remaining participants (8 females, 4 males) was 23.80 years (range 18 to 29 years), and their mean educational level was 15.42 years (range 12 to 17 years).

Participants had to complete two semantic knowledge tests: 1) the Mill Hill vocabulary test [21] in which participants had to choose synonyms for 34 items from a list of 6 words; 2) the WAIS-III Information subtest [22], with 28 questions assessing general knowledge. They also completed two executive tests: 1) the Stroop test [23], commonly used to assess inhibition abilities. Two subtests were used, color naming, in which participants had to name the color of crosses as quickly as possible in 45 s, and color-word interference, in which they had to name the color of the printed words in 45 s. The number of correct responses in 45 seconds was recorded and the score was computed as follows: [(color naming condition score – color-word interference score) / color naming condition score]. 2) A verbal fluency task, in which participants were asked to say aloud all the words they could think of beginning with the letters P, R and then V, in one minute.

The experiment had one within-participant factor (Condition: read vs. generate), and consisted of two study/test blocks, one for each condition (Generate vs. Read). The experimental material consisted of two lists of 60 pairs of six- to ten-letter French singular nouns for each learning condition (http://dico.isc.cnrs.fr/). The strength of semantic association between cue and target was moderate (as assessed by the on-line database http://dico.isc.cnrs.fr/; e.g. *LEAF - VEGETABLE*) and was comparable for the two lists, as were the frequency of occurrence and the number of letters in each pair of words. The learning condition was counterbalanced across lists and participants. Thus, each study list consisted of 60 word pairs, with 4 additional pairs at the beginning and the end of each list as primacy and recency buffers. Each test list consisted of 60 words (initial cues). All stimuli appeared on a computer monitor in white on a black background in upper case.

Once the electrode cap had been fitted, participants were seated comfortably in a chair in front of the stimulus presentation monitor. After a practice phase to familiarize them with the experimental procedure, including encoding and cued recall of 5 items for each condition, the first study/test block began. Each learning task started with a 500-ms presentation of a fixation cross, followed immediately by either a pair of words in the read condition (*LEAF – VEGETABLE*) or the cue and the target minus the last letters in the generate condition (*LEAF – VEGET__)* presented in the center of the screen for 1000 ms. In each learning condition, participants were instructed to pay attention to the words placed in second position, which they had to try to memorize. After 1500 ms, a question mark was displayed for 4000 ms. For the read condition, participants had to read aloud the word pairs, and in the generate condition, they had to generate aloud the incomplete word. In this later condition, all participants generated the target word in at least 90 % of the trials. The fixation cross then reappeared, indicating the start of the next trial. The retrieval task also started with presentation of a fixation cross for 500 ms, after which a cue (*LEAF* - _____) was displayed for 500 ms, centered on the position occupied by the fixation cue. After a period of 1500 ms, the question mark was displayed for 5000 ms for the response. Participants were instructed to try to remember the second word of the pair and if this was not possible, to produce the first suitable word that came to mind. As soon as the question mark appeared, two verbal responses were required: first the target word, and secondly “old” or “new” to indicate whether the word was a studied item or not. The old/new judgment included in this paradigm can allow dissociate among the production of non-target items those which are correctly judged as new and those incorrectly judged as old items (false alarms) [24]. In this study, because of the limited number of events in each condition, we decided not to dissociate responses according to this awareness.

The EEG activity was recorded with electrodes embedded in an elastic cap (Electro-cap International) from 62 scalp sites of the extended 10-20 system. The vertical Electro-Oculogram (EOG) was recorded from electrodes located above and below the director eye, and the horizontal EOG from electrodes at the outer canthus of each eye. All scalp electrodes were off-line referenced to both earlobes. EEG and EOG were recorded continuously within a band pass from 0.16 to 170 Hz and were A-D converted with 16-bit resolution at a sampling rate of 512 Hz.

Recording epochs were 3200 ms in length, with a 200 ms pre-stimulus baseline. ERPs recorded during encoding for subsequently correctly recalled items (Hits) were compared for the two conditions: read (mean number of trials: 27.92; range: 16-38) and generate (mean number of trials: 32.92; range: 22-43). Prior to averaging, each epoch was visually scanned for EOG and other artifacts. The averages were lowpass-filtered below 12 Hz in order to increase the signal-to-noise ratio. ERPs were quantified by measuring mean amplitude on 5 time windows: 300-600 ms, 600-900 ms, 900-1200 ms, 1200-1500 ms, 1500-1800 ms. Six groups of 6 electrodes were chosen for analyses, at anterior (left: F3, F5, F7, FC3, FC5, FT7; midline: F1, Fz, F2, FC1, FCz, FC2; right: F4, F6, F8, FC4, FC6, FT8) and posterior (left: P3, P5, P7, CP3, CP5, TP7; midline: P1, Pz, P2, CP1, CPz, CP2; right: P4, P6, P8, CP4, CP6, TP8) locations. Separate ANOVAs were conducted on the ERPs from the 2 midline sites, the 2 lateral anterior sites, and the 2 lateral posterior sites. These ANOVAs involved factors of Condition (read vs. generate), Location (anterior vs. posterior) and Laterality (left vs. midline vs. right). Only effects involving the Condition factor (generation effect) were reported. All post-hoc tests used the Newman-Keuls method, with a significance level of $p < .05$.

Results

Behavioral data

Performance was assessed through several indexes. The recognition rate was defined as the mean percentage of words correctly produced and recognized as studied words. The false alarm rate was the proportion of stems that were completed with a target word that had not been studied during the encoding phase but were incorrectly judged as old. The corrected recognition rate was computed by subtracting the false alarm rate from the recognition rate. Memory accuracy measures in each condition is summarized in Table 3. One-tailed *t*-tests showed that Condition had a marginally significant effect on the recognition rate and false alarm rate and a significant effect on the corrected recognition rate. Memory accuracy was significantly better for the generate condition than the read condition.

[Insert Table 1 about here]

ERP data

Figure 1 shows grand average ERP waveforms for Hits in the read and generate conditions at selected electrode sites and the scalp distribution of ERPs elicited by Hits in each condition is shown in Figure 2. Table 2 displays significant results of ANOVAs and post-hoc tests. ANOVAs gave rise to a main effect of Condition (read vs. generate) from 900 to 1800 ms, showing greater ERP magnitude for Hits in the generate than the read condition. Analyses also revealed an interaction of Condition with Laterality from 600 to 1500 ms. Post-hoc analyses in the 600-900 ms and the 900-1200 ms epochs indicated that ERPs for Hits were larger over the right hemisphere for the generate condition and more particularly in the read condition. In the 1200-1500 ms time windows, ERPs for Hits in the generate condition were smaller over the left hemisphere, whereas ERPs for Hits in the read condition were similar in the two hemispheres. In addition, ERPs for Hits were greater for the generate condition than the read condition at all hemispheric sites for the 900-1200 ms and 1200-1500 ms epochs only.

[Insert Figure 1 about here]

[Insert Figure 2 about here]

[Insert Table 2 about here]

Bravais-Pearson correlational analyses were then carried out to assess relationships between the ERP correlates of the generation effect, the behavioral generation effect, executive and semantic measures. An ERP generation effect was computed as the difference between ERPs for Hits in the generate condition and ERPs for Hits in the read condition, for each time window, for the frontal electrodes (average of right, midline and left frontal electrodes) and parietal electrodes (average of right, midline and left parietal electrodes). The behavioral generation effect resulted from the difference between the corrected recognition rates of the generate and the read conditions. In order to reduce the data, we carried out an Oblimin rotation (Varimax) principal component analysis on the four neuropsychological test scores (Mill Hill, Information, Fluency and Stroop tests). This factorial analysis revealed two factors, with the Mill Hill and the Information tests loading on one factor, interpreted as reflecting semantic knowledge, and the Stroop and the fluency tests loading on another, interpreted as reflecting executive abilities. On the basis of this factor analysis, we computed for each participant a semantic knowledge composite index, as the average of the standardized z-scores of the Mill Hill and Information tests (0.18; ±0.93), and an executive composite index, as the average of the standardized z-scores of the Stroop and fluency tests (0.06; ±0.73).

Correlational analyses indicated that the executive composite index was negatively correlated with the ERP generation effect on frontal areas (600-900 ms: $r = -.59$; $p<.05$) and parietal areas (600-900 ms: $r = -.61$; $p<.05$; 900-1200 ms: $r = -.49$; $p=.09$; 1500-1800 ms: $r = -.62$; $p <.05$), whereas no significant correlation appeared with the semantic knowledge composite index. Relationship between the composite executive index and the ERP generation effect is presented in Figure 3. Additional analyses on the behavioral index of the generation effect did not reveal any significant correlation with either executive (r = .22; NS) or semantic measures (r = .22; NS).

[Insert Figure 3 about here]

Discussion

The present study investigated the cognitive and neural processes associated with the generation effect. As predicted, and in agreement with previous behavioral studies, participants were more accurate in the retrieval of words that they self-generated during the encoding phase than those they simply read. It confirms the robust benefits of generation on memory performance [see 2 for a review]. In order to explore the neural correlates of this generation effect, we contrasted the electrophysiological activity associated with successfully encoded words studied under either a generate or a read condition. Our results showed greater ERP encoding-related activity for the generated than the read words, from 900 to 1800 ms post-stimulus, on middle and bilateral frontal and parietal electrode sites. This is consistent with the only two fMRI studies that have examined the neural basis of the generation effect, which showed greater activity under a generate than a read condition in a broad neural network including prefrontal and posterior cortical areas [9] or regions in frontal, anterior cingulate areas and the caudate nucleus and the temporo-parieto-occipital junction [10]. These regions associated with generation have been linked to different processes such as semantic processing, self-monitoring processes or executive control [9, 10, 19], suggesting that all these processes might be involved in self-generated memory encoding. In addition, this is the first study that has been able to examine the time course of this neural generation effect by using ERPs. Interestingly, we observed greater activity for the generate than the read condition only in the latest time windows, from 900 to 1800 ms. This finding suggests that similar neural processes may be involved in both conditions in the early period and that the additional processes allowing the benefit of generation occur later. They may reflect self-monitoring processes allowing participants to check their responses in the generate condition. Although the ERP difference between the two encoding conditions was widespread on the scalp, it was greater on right electrode sites. This may reflect the increased need for perceptive processes in the generate condition, as incomplete words may require a visual representation of the possible words [25]. However, these hemispheric differences must be interpreted with cautious since gender of our participants, which may influence condition-related hemispheric differences, has not been balanced [26].

In a further attempt to elucidate the cognitive processes involved in the generation effect, we performed correlational analyses to test two hypotheses that have been proposed to explain the generation effect. According to the semantic hypothesis, the benefit of generation comes from greater semantic activation for self-generated words, resulting in deeper processing [8]. The cognitive effort hypothesis proposes that generated words produce better memory performance than simply read words because they involve more resource-dependent processes. Our results revealed significant negative correlations between ERP activity associated with the generation effect and executive control measures (Frontal 600-900 ms; Parietal: 600-1200 ms and 1500-1800 ms) but not with the measure of semantic knowledge. This suggests that participants with lower executive control abilities benefit the most from the generation process at a neural level. Given their limited resources, these participants may not be able to initiate elaborate encoding processes spontaneously in the read condition, whereas the instruction in the generation condition may drive them to engage more neural resources. This is in agreement with studies in the aging literature showing that older adults, because of their impaired executive abilities, have difficulty engaging self-initiated processes, but that the generation condition drives them towards more efficient memory strategies, in particular when the rule is semantic, as was partly the case in our paradigm [4]. This finding supports the idea that the involvement of executive control processes is one of the key mechanisms of the generation effect. Nevertheless, correlations between the behavioral generation effect and either executive or semantic measures were not significant. Thus, even though the ERP generation effect (more resources engaged in the generate than the read condition) was greater among participants with lower executive abilities, it may not be sufficient to give rise to a behavioral benefit. In addition, the lack of statistical power due to the small number of participants might also have reduced the possibility of observing significant effects in the present experiment, and it would be interesting to replicate these findings with a larger sample. The difference between the correlational patterns of behavioral and ERP measures may also be due to the fact that the latter are more sensitive. By contrast, the semantic index was not related to the generation effect, which seems to suggest that these semantic abilities might not have been the most involved in our task. Nevertheless, it should also be borne in mind that cognitive effort and the semantic hypothesis are not mutually exclusive, some authors suggesting that semantic processing is a control process [27]. One limitation of this study is the moderate number of participants, which may have limited the possibility of observing significant findings. Thus, it would be interesting to reproduce our findings with a larger sample size, in order to increase statistical power.

Further studies are needed to specify the neural and cognitive mechanisms and to disentangle the different hypotheses. It would be interesting to include other measures of semantic knowledge to assess semantic activation abilities more directly. In addition, the cognitive processes involved in generation are likely to vary according to the nature of the task. Increasing task difficulty for instance by including more to-be-learned items in the paradigm or by varying the nature of the cue-target association rule would also allow the ERPs for forgotten items to be used. This would allow us to investigate the ERP subsequent memory effect (difference between ERP activity for remembered and forgotten items) and thus to examine the effects of generation on the neural correlates of successful encoding processes. A complementary approach for tracking these neural correlates of successful encoding would be to use spectral analysis in order to examine the effects of generation of patterns of oscillatory brain activity [for a review see 28].

Conclusion

This study improves our understanding of why generation enhances memory performance. It suggests that generation is associated with greater later neural activity, suggesting the use of additional processes. Our findings also provide evidence in support of the cognitive effort hypothesis of the generation effect.

Acknowledgements

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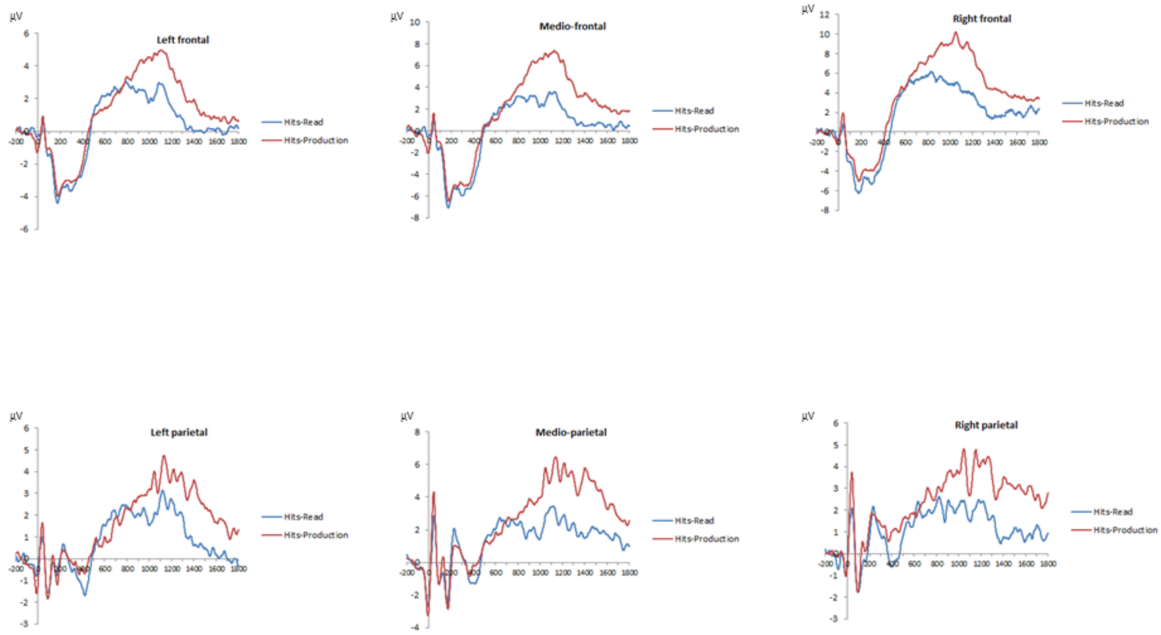

Fig. 1: Grand average ERPs associated with Hits (items subsequently recalled) at left frontal, middle frontal, right frontal, left parietal, middle parietal and right parietal sites in the generation condition and the read condition.

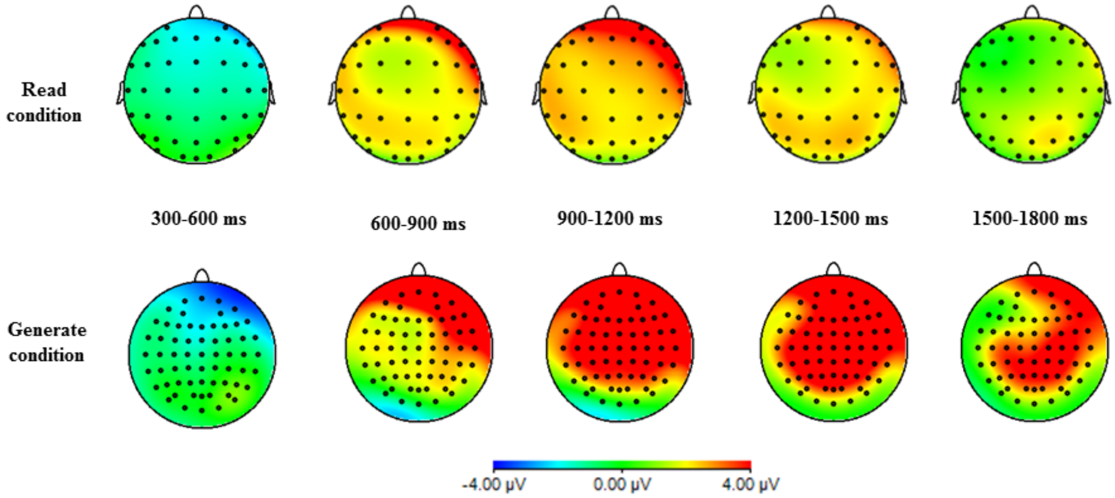

Fig. 2: Topographic voltage maps showing scalp distribution of ERPs associated with Hits (items subsequently recalled) in the read condition and the generate condition, for the 300-600 ms, 600-900 ms, 900-1200 ms, 1200-1500 ms and 1500-1800 ms time windows.

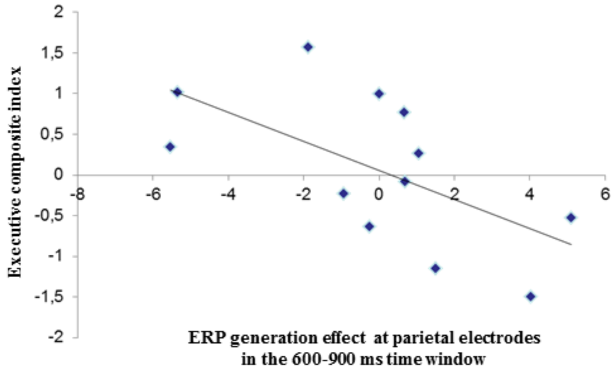

Fig. 3: Scatter plot showing the relationship between the ERP generation effect at parietal electrode sites in the 600-900 ms time window and the composite executive index.

Table 1: Memory accuracy measures in each condition

	Read condition	**Generate condition**	**t**
Recognition rate	56.11 (12.48)	59.86 (11.36)	$t(11)$ =-.87, p = .08
False alarm rate	3.75 (3.77)	6.53 (6.25)	$t(11)$ = 2.06, p = .06
Corrected recognition rate	46.67 (15.84)	53.19 (12.03)	$t(11)$ = -2.39, $p < .05$

SDs are shown in parentheses.

Table 2: Significant results of ANOVAS on ERP data in each time window

	300-600 ms	600-900 ms	900-1200 ms	1200-1500 ms	1500-1800 ms
Condition	*F*(1,11) = 1.35]	*F*(1,11) = 0.01	*F*(1,11) = 13.82, *p*<.01	*F*(1,11) = 24.01, *p*<.001	*F*(1,11) = 8.14, *p*<.05
Condition × Laterality	*F*(2,22) = 1.68	*F*(2,22) = 3.58, *p*<.05	*F*(2,22) = 3.14, *p*=.06	*F*(2,22) = 4.17, *p*<.05	*F*(2,22) = 1.09
Post-hoc analyses					
Read condition					
Left vs. Right		*F*(1.11) = 6.71, *p*<.05	*F*(1.11) = 8.29, *p*<.05	*F*(1.11) = 1.42	
Left vs. Middle		*F*(1.11) = 0.001	*F*(1.11) = 0.22	*F*(1.11) = 1.23	
Right vs. Middle		*F*(1.11) = 9.72, *p*<.01	*F*(1.11) = 9.72, *p*<.01	*F*(1.11) = 0.38	
Generate condition					
Left vs. Right		*F*(1.11) = 0.39	*F*(1.11) = 17.60, *p*<.01	*F*(1.11) = 11.24, *p*<.01	
Left vs. Middle		*F*(1.11) = 10.22, *p*<.01	*F*(1.11) = 9.03, *p*<.05	*F*(1.11) = 13.10, *p*<.01	
Right vs. Middle		*F*(1.11) = 13.77, *p*<.01	*F*(1.11) = 7.46, *p*<.05	*F*(1.11) = 0.02	