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The age-related effect on electrophysiological correlates of successful episodic memory encoding supports the hypothesis of a deficit in self-initiated encoding processes in aging

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Abstract

Episodic memory decline with aging may be due to an age-related deficit in encoding processing, older adults having increasing difficulty to self-initiate encoding strategies that support later retrieval. Using event-related potentials (ERPs), the present study explored for the first time the neural correlates of successful encoding in a resource-dependent episodic memory task, in which participants had to self-initiate processes at both encoding and retrieval. At the behavioral level, results confirm the better memory performance of young than older adults. Comparing the neural activity elicited by studied items that were and were not subsequently recalled (Subsequent Memory Effect, SME), electrophysiological data revealed that younger adults showed a significant and sustained SME, shifting from parietal to frontal areas, suggesting that they self-initiated deep encoding strategies. In older adults, the duration of brain activity was shorter and located more in the parietal than frontal areas, suggesting that they used shallow rather than deep processes. Consistent with the hypothesis of a deficit in self-initiated strategies in aging, our findings suggest that when older adults are faced with a difficult memory task (no encoding support and no cue at retrieval), they engage fewer elaborative strategies than young adults, resulting in impaired episodic memory performance.

Keywords: Episodic memory, aging, ERPs, encoding strategies

Introduction

Episodic memory declines with advancing age [1, 2]. However, according to the environmental support hypothesis [3], age-related differences in episodic memory are particularly pronounced in tasks thought to be more resource-dependent, particularly those requiring self-initiated processing at encoding and/or retrieval stages [4, 5]. Age-related difficulties in strategy implementation can be reduced by giving older adults instructions at encoding that guide them towards elaborate processing [4, 5, 6, 7] or cues that facilitate retrieval [2, 8, 9, 10]. The present study examines the hypothesis that age-related episodic memory impairments are mainly due to difficulty self-initiating encoding and retrieval processes.

Unlike behavioural studies, imaging data make it possible to examine brain activity involved in encoding and retrieval separately. To examine the neural correlates of successful memory encoding, the main paradigm consists of comparing the neural activity elicited at encoding by studied items that are subsequently remembered (Hits) with those that are not retrieved (Misses) (Subsequent Memory effect “SME”) [11, 12]. Thanks to their high temporal resolution on a millisecond (ms) scale, event-related potentials (ERPs) make it possible to examine the time course of the neural mechanisms underlying encoding processes. SME, as an electrophysiological indicator of successful encoding, is characterized by greater ERP magnitude for Hit than Miss items, appearing from about 400 ms post-stimulus and lasting for several hundred milliseconds, widely distributed on the scalp across the frontal, central and parietal regions [13, 14, 15, 16, 17].

SME depends on the level of processing at encoding and is stronger when encoding requires deep (semantic) than shallow (perceptual) processing [12]. Studies manipulating the level of processing have proposed two topographic components: perceptual encoding involving more posterior activity, and semantic encoding involving more frontal pole regions [16, 18, 19, 20,

21]. This suggests that semantic processing involves more elaborate and complex processes, as the frontal lobe is associated with the implementation of effortful memory strategies [16], and is consistent with the idea that semantic processing leads to better memory performance [7].

Successful encoding is also affected by aging. Comparing perceptual and semantic encoding, Kuo et al. [22] found that young adults showed a significant SME in both conditions up to 1000 ms, whereas in older adults SME remained significant only for the semantic condition after 550 ms, with widespread distribution over the scalp that was smaller in the frontal regions. The authors concluded that the age effect was stronger for perceptual than semantic tasks. Friedman et al. [23] found a divergent result, as only young adults showed a significant SME of between 300 to 1300 ms post-stimulus, which was not modulated by the nature of the task. The lack of significant effect in older adults was explained by the high variability in SME magnitude and delay in older adults. When the encoding task was perceptually oriented, Gutchess et al. [24] found significant frontocentral SME between 300 and 900 ms post-stimulus in young and older adults. This significant and lasting SME in older adults, even when the encoding task was perceptually oriented, could be partially explained by the fact that pictures of scenes engage semantic processing [25, 26], and also by the incidental nature of the task. Indeed, studies have shown more age-related differences in neural activity during intentional than incidental tasks, consistent with the hypothesis of an age-related deficit in self-initiated encoding strategies [27, 28].

Finally, in two studies examining age differences, participants performed an intentional memory task without guidance at encoding but with strong support at retrieval (recognition task). Friedman and Trott [15] investigated SME in relation to the recollection-know paradigm [29]. They found a significant SME at all scalp locations from 400 ms and up to 1100 ms in both groups. Group differences appeared between 400 and 800 ms post-stimulus,

both young and older adults showing reliable SME for recollection, whereas only the older participants showed an SME for familiarity, suggesting poorly differentiated encoding processes as they made no difference between items subsequently associated with an encoding context and those associated with a feeling of familiarity. Kuo [30] also found a significant SME between 360 and 700 ms in older adults and suggested that this effect corresponded to an attempt to encode items semantically without elaborative processing. The author suggested that the early SME reflects updating of working memory, whereas the late positive component (after 700 ms) could indicate deep processing such as binding of concepts. Thus, the short SME observed could reflect a deficiency in elaborative processing, consistent with the idea that older adults have difficulty self-initiating efficient encoding strategies when no guidance is provided.

Overall, results indicate that aging affects the pattern of SME, with young adults showing consistently significant and longer SME [15, 22, 23, 24, 30], while for older adults, SME is reduced and/or shorter [22, 30] or insignificant [23]. The SME pattern seems less affected by age when encoding is associated with a semantic instruction and also when retrieval is driven by a cue, and is more affected when less guidance is provided. Given their limited resources [6], older adults have difficulty self-initiating memory processes and require more environmental support such as explicit instructions to process items. Almost all the studies that have examined age-related differences in SME have provided environmental support at encoding (semantic or perceptual directions) and at retrieval (recognition or cued-recall tasks). The only studies [15, 30] that have investigated SME when no instruction was given, requiring participants to self-initiate encoding processes, showed significant but reduced and undifferentiated (between recollection and familiarity) SME in older adults. However, Friedman [15] instructed participants to study lists of sentences, providing some semantic help at encoding, and memory performance was evaluated through a recognition task that

could also be considered as an environmental aid at retrieval. In Kuo's study [30], only older adults were instructed to memorize and subsequently recognize Chinese characters, therefore age-related differences could not be examined. There is thus a lack of data in the literature about age-related differences in the ERP correlates of successful encoding in young and older adults in more resource-dependent episodic memory tasks, in other words, when participants have to self-initiate processes both at encoding (no encoding support) and at retrieval (free recall). New data could provide important insight into changes in SME in aging. ERPs could also be used to examine the hypothesis that older adults have a deficit in self-initiating processes.

The aim of this study was to improve understanding of the effects of aging on the ERP correlates of encoding processes. More precisely, we explored ERP activity while participants encoded lists of words without any instruction, followed by a free-recall task. Since advancing age is associated with reduced resources to engage efficient encoding and retrieval processes spontaneously, we expected to observe reduced or insignificant SME in older adults and more parietal distribution, reflecting the self-initiation of more shallow than deep processes. Given that younger adults are more likely to self-initiate memory processes to encode and retrieve information, they should show more significant and frontal SME, suggesting implementation of effortful processes.

2. Method

2.1. Participants

The sample consisted of 36 right-handed native French speakers, with 19 young adults aged between 20 and 40 ($M = 26.31$ years, $SD = 5.05$), 64% women, and 17 older adults aged between 60 and 70 ($M = 64.29$ years, $SD = 2.46$), 70% women. The groups did not differ significantly in educational level (young adults: $M = 15.05$ years, $SD = 2.19$; older adults: M

= 13.41 years, SD = 3.77; $t(34) = 1.61$, $p=.11$). Older adults had higher vocabulary scores (Mill Hill vocabulary test) [31] than young adults (young adults: $M = 25.63$, $SD = 4.32$; older adults: $M = 28.64$, $SD = 2.44$; $t(34) = -2.53$, $p = .016$), confirming that older adults have a higher level of cultural knowledge than younger ones. Participants had no history of brain injury, cardiovascular disease, psychiatric disease or alcoholism, and had normal or corrected-to-normal vision. None of them were on medication known to affect the central nervous system. All had scores below the cut-off of 11 on the two subscales of the Hospital Anxiety and Depression Scale (HADS) [32]. Participants aged 60 years and over scored above the cut-off of 27 on the Mini-Mental State Examination (MMSE) [33], suggesting that they were not suffering from cognitive impairment. The study was approved by the local ethics committee of the University of Tours, and all participants signed consent forms and received financial compensation (30 euros) to acknowledge the time they spent participating in the study.

2.2. Material and procedure

Participants carried out an episodic free-recall task. First, they were seated comfortably and fitted with an electrode cap. They were then instructed to memorize four lists of three- to ten-letter singular French nouns for a subsequent free-recall test. The experimental material was extracted from the French database “LEXIQUE” [34]. The number of letters per word was comparable between the lists, as was the frequency of occurrence. There were four successive study-test blocks, each composed of (i) an encoding phase in which a list of 20 words in upper case were presented on a screen one at a time in random order, (ii) a 30-second back-counting task in steps of three to reduce the recency effect, and (iii) a free-recall task. The encoding phase (see Figure 1) started with a 1000-ms presentation of a fixation cross, followed by a word that participants were asked to memorize, presented for 1000 ms. A fixation point was then displayed for 1000 ms during which time participants could process the word. A large

fixation cross was then presented for 1500 ms indicating the end of the trial. All stimuli were presented in white on a black background. After each encoding phase, participants performed the back-counting task and were then asked to say all the words they could remember, with no time limit. Participants first carried out a familiarization phase with a short block of five items.

Continuous EEG activity was recorded from 62 scalp sites using an electrode system fixed in an elastic cap, in accordance with the international 10-20 system [35]. Recorded activity was referenced online to linked mastoids, and a ground electrode was placed on an anterior site (AFZ). Vertical electrooculogram (EOG) was recorded from an electrode placed below the right eye and horizontal EOG from two electrodes, one at the outer canthus of each eye. The EEG and EOG signals were sampled continuously at 512 Hz and band-pass filtered between 0.25 and 30Hz.

2.3. Data analysis

Behavioral data

Three memory scores were calculated: a hit rate (proportion of correctly recalled words), a false alarm rate (proportion of recalled words that were not in the studied lists), and a corrected hit rate corresponding to the hit rate minus the false alarm rate. We conducted *t* tests to compare the performance of the young and older adults on the memory task.

ERP data

Offline data were segmented with epochs including a 200-ms pre-stimulus baseline and a 2500-ms post-stimulus interval. Blink artifacts were corrected using Gratton and Coles' algorithm [36], and trials containing muscular or other recording artifacts were rejected manually. ERPs were averaged separately for each group and for hit items (subsequently

remembered study items) and miss items (subsequently forgotten study items) with a minimum number of 16 artifact-free trials for each item category. Based on previous literature [14, 15, 18], mean ERP amplitudes were quantified in four latency windows (400-700 ms, 700-1000 ms, 1000-1300 ms and 1300-1600 ms post-stimulus) and at six electrode sites. For each site, the average of two electrodes was calculated: right frontal (F6, FC6), midline frontal (Fz, FCz), left frontal (F5, FC5), right parietal (P6, CP6), midline parietal (CPz, Pz) and left parietal (P5, CP5).

ANOVAs were conducted for each latency window, with item type (hit vs. miss), location (parietal vs. frontal), and laterality (right, midline, left) as within-participant factors, and group (young vs. older) as between-participants factor. Secondly, when global interaction was significant, within-group comparisons explored changes in the hit/miss effect pattern. Given that we were interested in the hit/miss effect, we will describe only significant main effects or interactions from ANOVAs involving the item-type factor. Post-hoc tests were carried out using the Newman-Keuls method (significance level of $p < .05$), a stepwise procedure used to carry out all the pairwise comparisons while considering the multiple comparisons performed successively.

3. Results

3.1. Behavioral data

Episodic memory. We performed *t*-tests to compare the two groups on the hit rate, the false alarm rate and the corrected hit rate. For the hit rate (young group: $M = 0.44$, $SD = 0.11$; older group: $M = 0.34$, $SD = 0.12$), results revealed that the young group recalled significantly more words than the older group, $t(34) = 2.41$, $p = .02$, Cohen's $d = 0.86$. The difference in false alarms was roughly significant (young group: $M = 0.02$, $SD = 0.03$; older group: $M = 0.05$, $SD = 0.04$; $t(34) = 2.02$, $p = .05$, Cohen's $d = 0.84$), with more false alarms in the older group.

Finally, the effect of group on the corrected hit rate confirmed that the young group performed better than the older group (respectively $M = 0.41$, $SD = 0.11$; $M = 0.28$, $SD = 0.12$; $t(34) = 2.98$, $p = .005$, Cohen's $d = 1.12$).

3.2. ERP data

Fig. 2 shows grand average ERP waveforms associated with Hit and Miss items at selected electrode sites in young and older adults, and Fig. 3 shows the scalp distribution of ERPs associated with Hit and Miss items for young and older adults.

400-700 ms time window

A significant effect of item type indicated that hit items elicited an overall higher voltage than miss items (classic positive SME) (see Table 1). The interaction between item type, location and laterality revealed that the SME differed according to location and laterality. Additional ANOVAs and post-hoc analyses were performed to clarify this interaction. Results showed that the SME was significant and of the same amplitude at left, midline and right parietal sites, whereas it was significant only in midline electrodes in frontal areas. At midline, it was similarly significant at parietal and frontal locations. No interaction including group factor was significant in this time window.

700-1000 ms time window

The interaction between item type, location and laterality was significant, as was the interaction between item type, location, laterality and group. Within-group analyses were carried out to further clarify these interactions. In the young group, the significant interaction between item type, location and laterality showed that item type was significant only at the

central frontal site. In the older group, no main effects or interactions were found to be significant.

1000-1300 ms time window

Three interactions appeared to be significant: between item type and location, between item type and laterality, and between item type, location, laterality and group. Separate analyses were carried out in the two age groups to clarify these interactions. In the young group, item type interacted with laterality and with location and laterality. Post-hoc analyses showed that item type was significant only in midline electrodes at the frontal site. For the older group, there was no significant main effect or interaction involving item type.

1300-1600 ms time window

The interactions between item type and laterality and between item type, location, laterality and group were significant. Post-hoc analyses were computed and indicated that item type interacted with location, laterality and with location and laterality in the young group. Item type was significant at the frontal site in midline and right areas, with a predominance at midline, whereas at the parietal sites it was only significant on the right. Moreover, on the right, the item type effect was predominant at the frontal site. Again, there was no significant main effect or interaction involving item type in older adults.

4. Discussion

The aim of the present study was to examine age-related differences in neural processes underlying encoding processes. This is the first study to investigate the ERP correlates of successful encoding processes in young and older adults when carrying out a highly resource-dependent intentional episodic memory task requiring participants to self-initiate encoding and retrieval processes. Consistent with the abundant literature in the field of episodic

memory aging, we observed that older adults retrieved fewer words than young adults [1, 2]. Our results showed age-related differences in SME, with longer ERP encoding-related activity for young than older adults. In both groups, a significant SME was observed from 400 to 700 ms post-stimulus at parietal areas (left, midline and right electrodes sites) and at the midline frontal electrode site. This finding suggests that similar neural processes were self-initiated by both groups in the early period, which could reflect implementation of perceptual processes associated with engagement in semantic processing [18, 19, 20, 21]. The significant frontal SME in both groups suggests that access to semantic processing is preserved in older adults. However, from 700 to 1600 ms, SME was only observed in young adults and with a frontal predominance. As frontal regions seemed to play a key role in the implementation of strategic processes required for encoding and retrieval [16], this longer frontal brain activity is compatible with the hypothesis that young adults spontaneously implement longer deep and controlled processing than older adults. These additional processes allow them to outperform older adults [16]. The lack of a significant SME in older adults after 700 ms suggests that even if access to semantic processing is preserved it is the elaborative and strategic processes that are adversely affected. This result supports the hypothesis of a deficit in self-initiated processes with advancing age, suggesting that older adults, due to their limited resources, have more difficulty initiating efficient processes when no environmental support is given, such as explicit directions to process items for meaning [3, 4, 5, 8].

Age-related neural changes associated with encoding have also been demonstrated in studies using positron emission tomography to compare cerebral blood flow (CBF) in young and older adults during encoding. They found that older adults showed little frontal brain activity. This age-related difference in blood flow is interpreted as reflecting less efficient processing with advancing age [27, 28]. The decline of CBF in the frontal cortex with advancing age has also been observed with single-photon emission computed tomography [37]. The episodic

memory deficit in older adults appears to reflect senescent changes particularly in the prefrontal cortex, which corroborates our ERP results and our hypothesis that aging is accompanied by a deficit in self-initiated encoding strategies. The greater vulnerability of anterior regions with aging has also been confirmed by positron emission tomography studies that used fluorodeoxyglucose to examine regional glucose metabolism as an indicator of brain activity. They reported greater age-related hypometabolism in anterior regions [38, 39] and suggested that this is related to cognitive decline [40].

How can our data help understand age-related differences in encoding processes compared to previous studies that have examined SME using different methods? Apart from the studies by Friedman et al. [23], who found no significant SME in older adults, and Gutches et al. [24], who found no reliable age-related differences, the other ERP studies converge towards significant but impaired neural correlates of encoding processes in older adults. When older participants have to self-initiate encoding and retrieval processes, as in our study, they show significant but shorter and more posterior SME. This pattern of results is similar to that observed when they are given a perceptual encoding task. For example, Kuo et al. [22] reported shorter SME in a perceptual task in older adults and with less frontal distribution. This confirms behavioral data indicating that when no aid is given to encode new information, older participants tend to self-initiate shallow and more inefficient processes rather than deep and elaborative processes. Our results are also consistent with studies that examined SME when participants had to self-initiate encoding processes before a subsequent recognition task. Unlike Kuo [30], whose study included only older adults and found a significant but short SME, our results reveal that while the SME pattern of older adults reflects the difficulty of the memory task, that of younger adults indicates that they were able to cope with difficulty, as the SME was longer, which is compatible with the implementation of self-initiated semantic

strategies (frontal distribution). The older adults in our study showed brain activity of a shorter duration than those in Friedman and Trott's [15] study. This difference can be attributed to the material used in their study; although the task did not include any environmental support, using sentences could have directed the participants towards semantic encoding. This interpretation is plausible, as the duration of the SME was similar to that observed in experiments that guided participants towards a semantic encoding process. However, both studies found that the older group showed less frontal brain activity than the younger group, reflecting their difficulty maintaining, integrating and coordinating information.

Finally, the negligible SMEs recorded in the older group could also be explained by the difficulty of the retrieval task used in our study. Indeed, the SME is based on retrieved items, and access to a previously encoded item is more difficult in a free-recall than in a recognition task, particularly in older adults due to their retrieval difficulties. Thus, it is possible that some items were correctly encoded but not recalled with the free-recall task (whereas they may have been recognized in a recognition task). However, these items were considered as misses, which can explain why there appeared to be less difference between hit and miss items (SME effect) in older adults. In order to confirm these interpretations, it would be interesting to conduct a study manipulating environmental support at both encoding and retrieval.

In sum, this study demonstrates that processes associated with successful memory encoding differ between young and older adults. Hence, when the memory task is effortful because encoding and retrieval require self-initiated processing, older adults engage fewer specific encoding processes than young adults, resulting in shorter SME and impaired episodic memory performance.

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-Declarations of interest: none

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Figures legends:

Figure 1: Visual depiction of the sequence of events in the encoding memory task

Figure 2. Grand average ERPs waveforms associated with Hit and Miss items at left frontal, frontal midline, right frontal, left parietal, parietal midline and right parietal sites in young and older adults

Figure 3. Topographic voltage maps showing scalp distribution of ERPs associated with Hits and Miss items for young and older adults for the 400-700 ms, 700-1000 ms, 1000-1300 ms and 1300-1600 ms time windows.

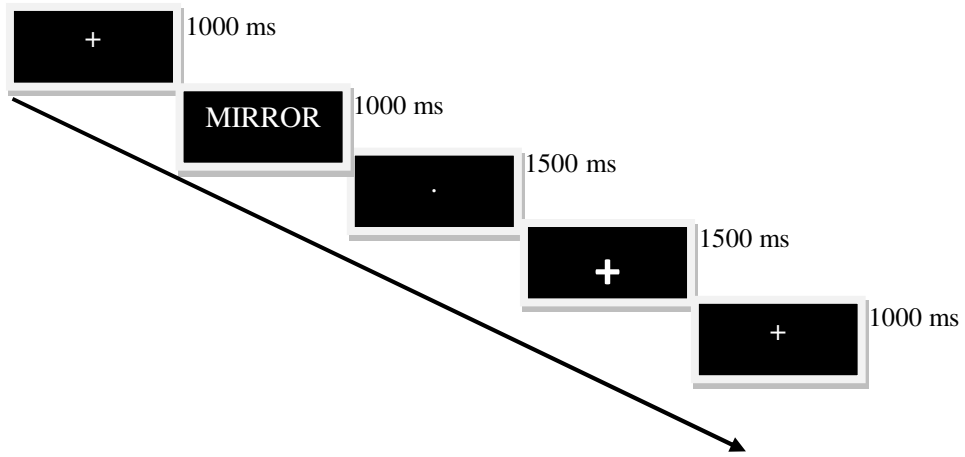
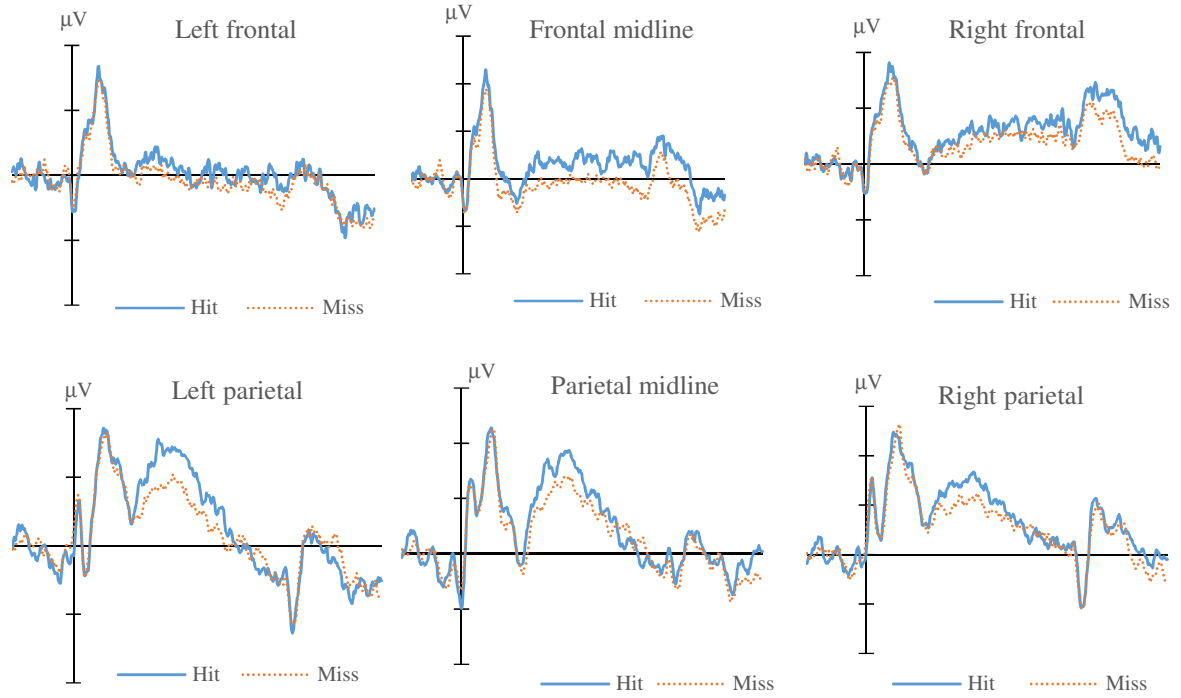
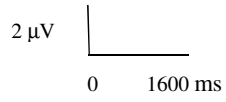
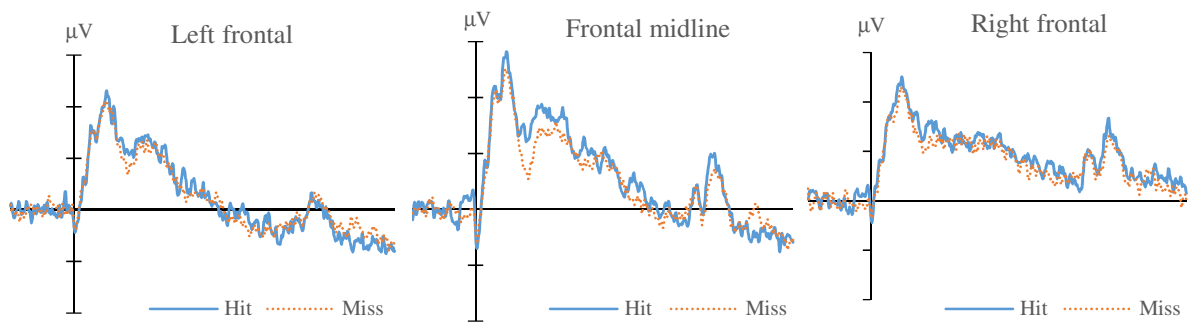
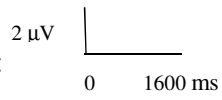


Figure 1: Visual depiction of the sequence of events in the encoding memory task

Young :



Older :



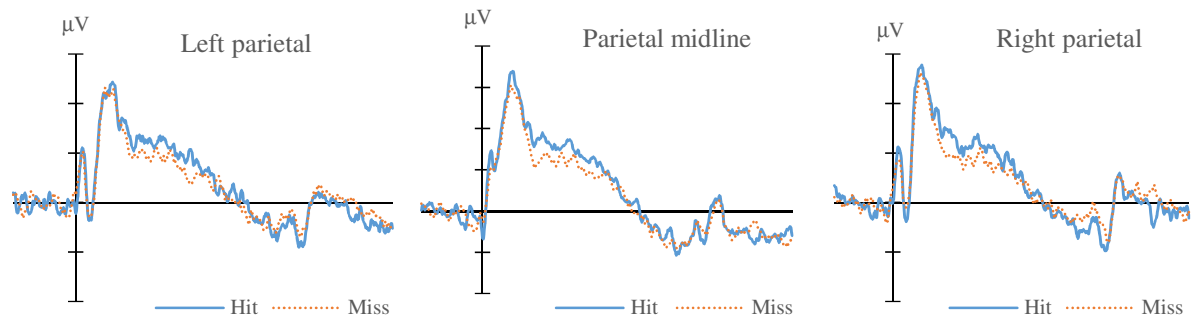


Figure 2. Grand average ERPs waveforms associated with Hit and Miss items at left frontal, frontal midline, right frontal, left parietal, parietal midline and right parietal sites in young and older adults

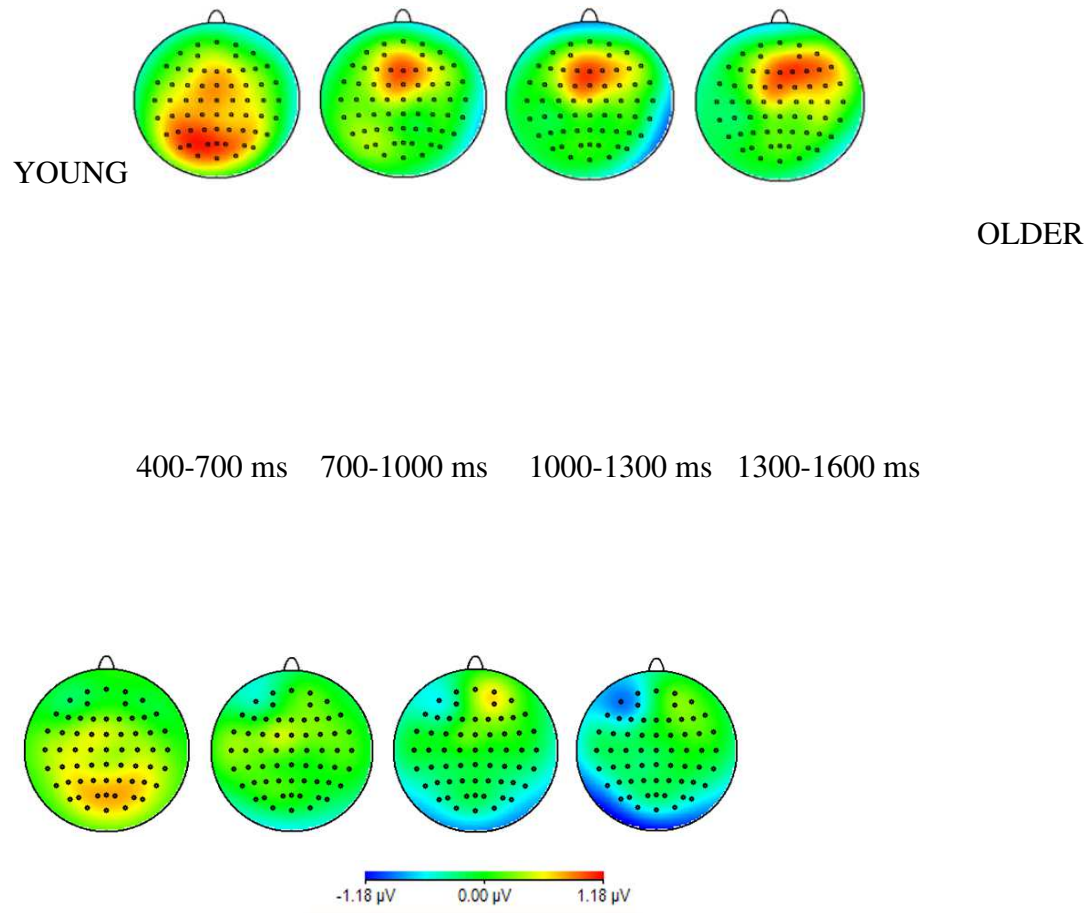


Figure 3. Topographic voltage maps showing scalp distribution of ERPs associated with Hits and Miss items for young and older adults for the 400-700 ms, 700-1000 ms, 1000-1300 ms and 1300-1600 ms time windows.

Table 1: Significant results of ANOVAS on ERP data in each time window

400-700 ms	
Item type	$F(1,34) = 6.28, p = .017, \eta^2 = 0.15$
Item type x Location x Laterality	$F(2,68) = 4.22, p = .018, \eta^2 = 0.11$
700-1000 ms	
Item type x Location x Laterality	$F(2,68) = 4.46, p = .015, \eta^2 = 0.11$
Item type x Location x Laterality x Group	$F(2,68) = 3.86, p = .025, \eta^2 = 0.12$
Young: Item type x Location x Laterality	$F(2,36) = 7.88, p = .001, \eta^2 = 0.30$
1000-1300 ms	
Item type x Location	$F(1,34) = 5.52, p = .024, \eta^2 = 0.11$
Item type x Laterality	$F(2,68) = 4.17, p = .019, \eta^2 = 0.11$
Item type x Location x Laterality x Group	$F(2,68) = 3.44, p = .037, \eta^2 = 0.09$
Young: Item type x Laterality	$F(2,36) = 5.21, p = .010, \eta^2 = 0.22$
Item type x Location x Laterality	$F(2,36) = 4.19, p = .022, \eta^2 = 0.18$
1300-1600 ms	
Item type x Laterality	$F(2,68) = 7.13, p = .001, \eta^2 = 0.17$
Item type x Location x Laterality x Group	$F(2,68) = 4.48, p = .014, \eta^2 = 0.11$
Young: Item type x Location	$F(1,18) = 5.36, p = .032, \eta^2 = 0.22$
Item type x Laterality	$F(2,36) = 8.90, p < .001, \eta^2 = 0.33$
Item type x Location x Laterality	$F(2,36) = 3.63, p = .036, \eta^2 = 0.16$