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Research Report

ERP correlates of intentional forgetting

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ABSTRACT

In this study we investigated the neurocognitive processes underlying the control of memory retrieval. In a Think/No-Think paradigm, adopted for the use in an event-related potential (ERP) experiment, participants learned word pairs and were subsequently presented with cue words and asked to either suppress or to recall the target word. During final cued recall tests for all initially learned targets, memory for the to-be-suppressed or to be-recalled items were tested. Memory for to be-recalled items was enhanced but no forgetting of to-be-suppressed items was obtained. The ERPs in the test phase were separated on the basis of prior learning success and failure, allowing separate analyses of strategic memory control, i.e. attempts to retrieve or to avoid retrieval and the outcome of these processes, i.e. successful retrieval and retrieval avoidance. An early P2 component and a parietal positivity were related to retrieval attempts and a centro-parietal N2 component was associated with attempts to avoid memory retrieval. The parietal positivity was attenuated for No-Think trials on learned items, for which item-specific memories exist. However, under the present testing conditions and in contrast to prior studies (Bergström, Velmans, de Fockert, Richardson-Klavehn, 2007) the parietal positivity was also sensitive to mere retrieval attempts. To examine whether similar neural systems are involved in the inhibitory control of unwanted memories and prepotent motor responses, a motor stopping experiment using a stop signal task was conducted with the same participants. Successful stopping was associated with an enhanced stop signal N2 that showed a similar centro-parietal scalp distribution as the aforementioned N2 to No-Think trials. As both components were significantly correlated, we assumed that some of the systems recruited to override prepotent motor responses are also involved to suppress memory retrieval.

1. Introduction

The human capacity of forgetting is a long-standing topic in psychological research since Ebbinghaus (1885). In memory research, forgetting has been traditionally treated as a memory failure that results from passive processing. From another point of view, intentional forgetting can be characterized as a strategic function of the cognitive system that allows us not to think about unwanted memories from our past, as for example emotional events or traumatic experiences that we would prefer not to remember. In this sense, intentional forgetting as an active cognitive process could be referred to as our ability to control the retrieval of unwanted memories. The current study focuses on one important aspect of memory

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control, namely, our ability to suppress specific information in a way that it cannot be retrieved from long-term memory.

Control of memory retrieval implies that voluntary processes can guide memory retrieval in order to selectively recover information relevant for current tasks and goals. The capacity to stop the retrieval of irrelevant information is a crucial aspect of controlled memory retrieval and some researchers assume that this form of control is supported by inhibitory mechanisms (e.g., Anderson 2005). In this view, inhibitory control is not only recruited to manage overt behaviour, but also to regulate internal processes, as for example when retrieval cues activate competing information in memory, or in order to reduce the activation level for prepotent memory representations, when they are not required. The link between intentional forgetting and inhibition implies that attempts to limit the activation of unwanted memories lead to an impairment of later retrieval. Research on this issue has been conducted over the last ten years in two memory situations: selective memory retrieval and memory stopping (Anderson, 2005).

Selective memory retrieval has been illustrated through the phenomenon of retrieval-induced forgetting (Anderson et al., 1994), in which the act of remembering may cause forgetting of related information in memory. In this paradigm, retrieval practice with some previously learned materials impairs recall of non-practiced items from the practiced categories. This memory impairment for non-practiced items has been attributed to an inhibitory control mechanism that promotes successful retrieval of the practiced items and inhibition of the non-practiced related items from the same category that act as competitors in memory during retrieval (Anderson et al., 1994; Anderson and Spellman, 1995; Bäuml and Aslan, 2004; Johansson et al., 2007).

Another forgetting phenomenon that presumably involves intentional inhibitory control is the voluntary avoidance of unwanted memories. Anderson and Green (2001) developed the Think/No-Think paradigm as an experimental procedure that allows to examine these processes. Subjects first learn weakly related word pairs. Next, in the Think/No-Think phase of the experiment they are represented with the first words of the previously learned pairs and are instructed to either recall the associated response word (right member of the word pair; the Think trials) or to not think about this word (No-Think trials). Think and No-Think trials are given either 0, 1, 8, or 16 times. In a final cued recall test, the subjects' memory is tested for the response words in two conditions. In a same probe test, the cue word of the learning phase is presented. In contrast, in the independent probe test subjects are provided with the name of a semantic category to which the response word belongs and its first letter. In both tests, participants are instructed to recall the associated response word.

The general finding from Anderson and Green (2001) is a linear decline of retrieval for suppressed items (No-Think trials) in both the same probe and independent probe tests, depending on the number of repetitions. This memory impairment indicates/implies that inhibitory control may be voluntarily recruited to prevent unwanted memories from coming to mind. Because the forgetting effect is also obtained in the Independent probe test, i.e. with recall cues that have not been presented in the learning phase, Anderson and Green (2001) argued that inhibitory control is applied to the unwanted memory itself, rather than disrupting or weakening the association between cue and response word. However, recently, several failures to find below baseline memory performance for No-Think items have been reported (Bergström et al., 2007; Bulevich et al., 2006; Hertel and Calcaterra, 2005). This suggests that forgetting effects are not a robust phenomenon and may depend on specific task situations (see Bulevich et al., 2006 for a discussion).

Using functional magnetic resonance imaging (fMRI) Anderson et al. (2004) investigated the brain region involved in the aforementioned effects. They found a network of brain regions showing greater activation during No-Think trials than during Think trials, including bilateral dorsolateral and ventrolateral prefrontal regions, the anterior cingulate cortex, and several premotor areas. This increased activation of prefrontal areas during suppression has been interpreted as a brain correlate of an active executive process that inhibits an unwanted memory. On the other hand, a bilaterally reduction of hippocampus activation was obtained for No-Think trials relative to Think trials, indicating that the amount of recollection is reduced in No-Think trials, i.e. when subjects attempt to prevent the associated word from entering consciousness at all. Moreover, a subsequent forgetting analysis for No-Think trials showed that the hippocampus and prefrontal regions interact during attempts to avoid unwanted memories.

A shortcoming of the aforementioned fMRI study is that, due its low temporal resolution, the fMRI technique does not allow to track the time course of the brain mechanism engaged by the attempts to forget or remember items in the Think/No-Think phase. Thus, the main goal of the present study is to examine the temporal characteristics of the brain mechanism initiated by Think and No-Think trials, using event-related potential (ERP) measures. ERPs have been successfully employed in episodic memory tasks and can be used as markers of memory processes and the associated control mechanisms (see Friedman and Johnson, 2000; Mecklinger and Jäger, 2009; Rugg and Wilding, 2000 for overviews).

The ERP correlate of recollection is a positive ERP at parietal regions, accentuated in the left hemisphere that extends from 400 to 800 ms after stimulus onset (Friedman and Johnson, 2000; Mecklinger, 2000; Smith, 1993; Smith and Halgren, 1989). This positive component is larger for correctly recognized items from a previous learning phase than for correctly rejected new items, and has been labelled the parietal old/new effect. (Rugg and Yonelinas, 2003; Wilding and Herron, 2006). Empirical support for the view that the parietal old/new effect is a correlate of recollection-based remembering comes from studies showing that the effect is larger for items associated with Remember judgments than with Know judgments (Smith, 1993), covaries with the amount of information retrieved (Vilberg et al., 2006) and is sensitive to the (recollection-based) retrieval of item-source associations (Jaeger et al., 2006). Moreover the parietal old/new effect can also reliably be recorded in cued-recall memory tasks, i.e. when the presentation of one part of an item pair serves as a retrieval cue for the other member of the pair (Jaeger et al., 2006; Rugg et al., 1996) These properties make the parietal old/new effect a valuable tool for examining the memory and control processes set in train by attempts to remember or forget previously learned items.

Capitalizing on these properties of the parietal old/new effect, Bergström et al (2007) recently examined the ERP correlates of retrieval and avoiding retrieval using the Think/No-Think manipulation. In addition the authors made the important distinction between strategies of retrieval or avoiding retrieval on the one side and the outcome of these strategies, i.e. successful retrieval and avoidance of retrieval on the other side. To accomplish this, the ERPs in the Think/No-Think phase were separated on the basis of prior learning success or failure. The logic was that strategic processes should be reflected in the ERPs irrespective of learning. In contrast, item-specific effects, retrieval success and successful avoidance of retrieval should only be reflected in the ERPs to those stimuli that are in principle retrievable, i.e. those which were initially learned. The main finding of the Bergström et al (2007) study was that a parietal positivity for learned Think trials was attenuated for learned No-Think trials and in the latter case not distinguishable from the waveforms to not learned trials. This suggests that retrieval of previously learned information in principal can voluntarily be avoided. In the present study we intended to replicate this finding. Therefore we adapted the method of classifying ERPs and analyzed the ERPs in the Think/No-Think phase on the basis of prior learning success or failure. If retrieval can successfully be avoided the parietal positivity should be attenuated in learned no-Think relative to learned Think trials, and the former condition should not differ from the ERPs elicited by not learned trials, i.e. words that cannot be retrieved because they have not been learned in the prior study phase.

Furthermore we aimed at tracking the time course of control processes in the Think/No-Think phase by identifying further ERP correlates of control over memory retrieval. We were in particular interested in whether the Think/No-Think paradigm engages processes (and their respective ERP correlates) which are also involved in other situations requiring cognitive control.

Control functions that either precede or occur in parallel with memory retrieval have repeatedly been investigated in ERP studies by examining the ERPs in test phases of recognition memory tasks. These studies revealed that ERP slow wave activity over frontal and parietal brain regions is correlated with different aspects of cognitive control helping to achieve selective memory retrieval. These processes comprise the adaptation of retrieval orientations in response to a retrieval cue (Rugg and Wilding, 2000; Werkle-Bergner et al., 2005), processes that guide the retrieval of item-context associations (Johansson and Mecklinger, 2003) or the control of competing memory traces (Johansson et al., 2007). On the basis of these finding we assume that ERP slow waves at frontal recordings may be sensitive markers for the control mechanisms initiated by attempts to remember or forget previously learned materials.

With respect to the temporal characteristics of cognitive control, we expected strategic and item specific control processes to be present before ERP correlates of retrieval (i.e. the parietal positivity) appear. The Think/No-Think task was adapted from procedures used to examine the stopping of motor responses, as for example the Go/No-Go task or the Stop Signal Task (Kok et al., 2004) a widely used procedure to examine the stopping of motor responses. ERP studies examining motor stopping consistently report fronto-centrally distributed N2 components, i.e. the NoGo N2 (Bekker et al., 2005; Bokura et al., 2001; Donkers and van Boxtel, 2004; Eimer, 1993; Falkenstein et al., 1999; Garavan et al., 2002) and the stop signal N2 (Band and van Boxtel, 1999; Logan et al., 1994; Schmajuk et al., 2006; van Boxtel et al., 2001; Ramautar et al., 2004). To the extent to which the control of motor actions and the control of internal actions (memory retrieval) rely on similar neural mechanisms, we expected that attempts to avoid unwanted memories in No-Think trials should elicit a similar N2 as in motor stopping paradigms.

In order to further explore the relationship between motor stopping and the suppression of memory retrieval more closely, we additionally conducted a Stop-Signal experiment with the same subjects. We expected the Stop-Signal N2 to correlate with the ERPs reflecting memory stopping.

2. Experiment 1

The experimental paradigm employed in our first study was a modified version of the Think/No-Think paradigm developed by Anderson and Green (2001). Subjects learned weakly associated word pairs (e.g. *Zeichnung* – *Vase*/chart – vase). Learning success was controlled for by including a relearning phase, in which participants had to recall the response word (the right hand word of each pair) upon presentation of the cue word (left hand word of each pair) until two thirds of the word pairs could be recalled correctly. Participants then performed a Think/No-Think task while EEG was recorded. On a trial-by-trial basis subjects were presented with a cue word (the left hand word of each pair) and were asked either to repeatedly recall and think about the pre-experimental associated response word (Think condition) or to prevent the associated word from entering consciousness at all (No-Think condition) for the entire presentation of the stimulus. One third of all word pairs was never shown in this phase and served as a baseline condition. In the final phase of the experiment, memory for words of all three conditions was tested in two cued recall tests, in which they were given the originally trained cue (same probe) or a novel test cue (independent probe). ERPs were calculated for both conditions during the Think/No-Think phase of the experiment separately for words that were learned and not learned in the prior study phase.

2.1. *Results*

2.1.1. *Behavioral data*

The mean percentage of learned trials after the test-feedback cycles was 68% and the analyses of memory performance in the final cued recall phase for both tests was conducted only for words pairs that were successfully learned. As illustrated in Fig. 1 recall was higher in the same probe than in the independent probe test. The proportion of recalled words was higher in the Think condition than in the Baseline condition in the same probe test. In the independent probe test, recall in the No-Think condition tended to be smaller than in the baseline condition. The mean probabilities of response words

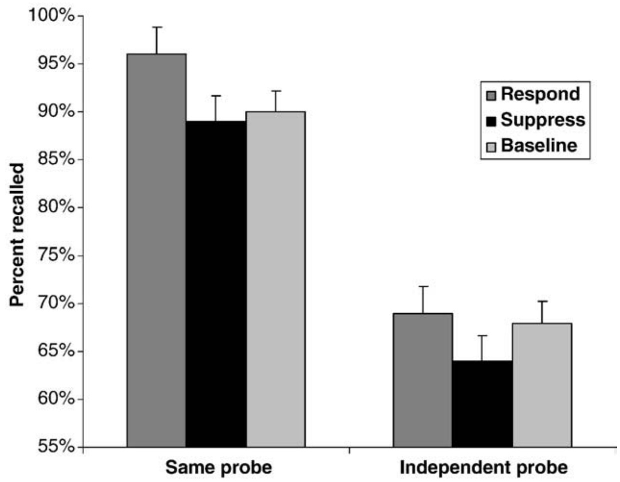

Fig. 1 – Final recall rates for the Same Probe (SP) and Independent Probe (IP) tests for previously learned word pairs. Recall was greater in the Think condition than in the Baseline condition for SP.

recalled on the final test were submitted to a repeated-measure ANOVA, with the within-subject factors Response condition (Baseline, Think No-Think) and test (Same probe, Independent probe). The ANOVA revealed a main effect of response condition (3) [$F(2,46)=4.25$, $p=.02$, $\varepsilon=0.98$], a main effect of Test [$F(1,23)=29.62$, $p<.0001$], indicating that memory performance was better in the Same Probe than in the Independent Probe test. As revealed by a contrast analysis, recall was higher in the Think condition than in the baseline condition [$F(1,23)=4.03$, $p=.05$.] No reliable forgetting effects, i.e. lower recall in the No-Think than in the baseline condition, were obtained (F-values <1).

The finding of reliable remembering effects (SP) is consistent with the data reported by Anderson and Green (2001). However, we did not get reliable forgetting effects. This may suggest that suppression effects are small and susceptible to individual and/or experimental variables (see Wessel et al., 2005; Bulevich et al., 2006 for a discussion). Therefore a follow up analysis was performed to examine potential factors that might have contributed to the absence of suppression effects. We assumed that the (high) semantic relatedness of the word pairs might have diminished suppression effects in the SP conditions. Therefore we median split all word pairs irrespective of learning success on the basis of the semantic relatedness scores derived from the pre-experimental rating study. After adding the factor to the ANOVA design we did not find any interaction between the factors Response Condition and Test and the Relatedness factor (F-values <1). By this, the absence of suppression effects in the SP condition cannot be accounted for by the high semantic relatedness of the word pairs in the present study.

2.1.2. *ERP data*

To allow separate analysis of strategic effects initiated by the Think and No-Think cues, i.e. attempts to retrieve and avoid retrieval of the target words and item specific effects, i.e. successful retrieval or retrieval avoidance, the learning status of the word pairs was taken into account in the ERP analysis of the Think/No-Think phase. The logic behind this analysis was that any strategic effects initiated by the Think and No-Think cues should be present irrespective of prior learning success or failure. Conversely, ERP correlates of successful retrieval or

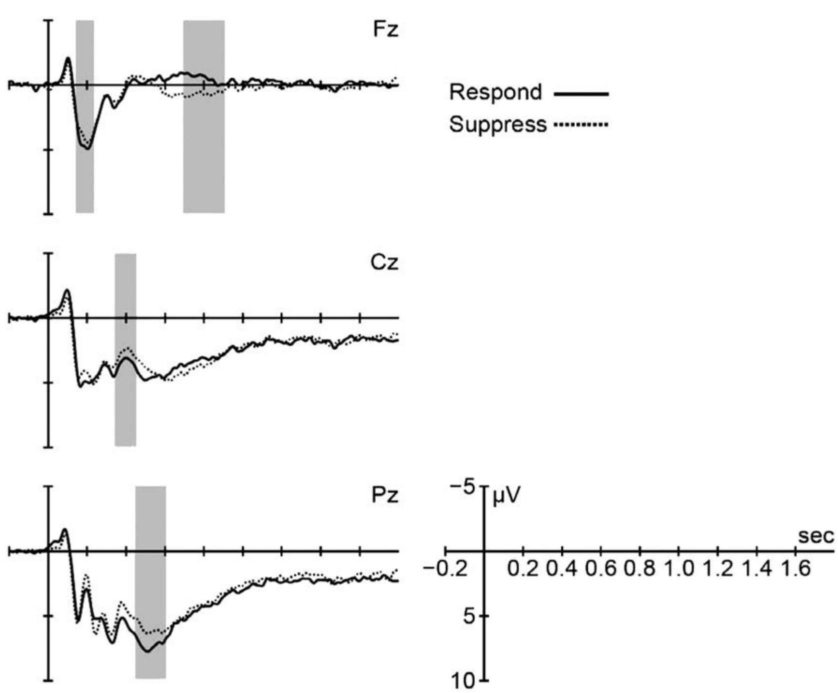

Fig. 2 – Grand average ERPs for the Think and No-Think condition during the Think/No-Think phase for all word pairs (irrespective of learning status) depicted at three frontal, central and parietal electrode sites. Shaded areas indicate the time windows used for statistical analyses.

retrieval avoidance should only be present for words that are retrievable in principle, i.e. those that were initially learned in the study phase. As cue words were presented 16 times with either Think and No-Think instruction, the ERPs for both conditions were averaged across these repetitions of cue words.

The grand average ERPs for the No-Think and Think condition derived from all word pairs of the study phase are depicted at the three midline electrodes, Fz, Cz and Pz. in Fig. 2. The ERPs elicited by No-Think and Think trials separated on the basis of prior learning success are illustrated in Fig. 3. As apparent from the figures, Think and No-Think trials elicit a P2 component that peaks at 204 ms and was larger for Think trials. The P2 was followed by a negativity at around 400 ms, with a centro-parietal maximum, that was enhanced for No-Think trials. As it resembles N2 components related to motor stopping it will be referred to as N2 in the following. A parietal positivity was obtained that started at around 450 to 600 ms and showed a Think>No-Think pattern. Partly overlapping with the parietal positivity, an effect of condition with reversed polarity (Think<No-Think) was obtained at frontal recordings between 700 and 900 ms. The scalp distributions of the P2, the N2, the parietal positivity and the late frontal effect elicited by all word pairs, irrespective of learning status are illustrated in Fig. 4. Starting around 700 ms, another effect with a broad topographical distribution emerged: It took the form of more positive going waveforms for learned than for not-learned trials irrespective of Response condition.

ERP waveforms in the Think/No-Think phase were quantified by measuring the mean amplitudes in four time windows (150–220 ms, 350–450 ms, 450–600 ms and 700–900 ms). The times windows were derived after visual inspection of the waveforms and were intended to quantify the P2, N2, parietal positivity and frontal positivity, respectively. A global ANOVA with the factors Condition (Think, No-Think) Learning Status (learned vs. not-learned) × Time Window (150–200 ms, 350–450 ms, 450–600 ms, 700–900 ms) × Region (frontal, central, parietal) × Laterality (left, middle, right) yielded significant interactions between Condition, Time Window, Region and Laterality, [$F(12,276)=3.46$, $p=.006$], Condition, Time Window and Laterality, [$F(6,138)=4.70$, $p=.002$]. Moreover a marginally significant interaction between Learning Status and Time Window, [$F(3, 69)=2.72$, $p=.058$] was found. This suggests, that the ERP waveforms for learned and not-learned materials in both conditions varied across time windows and electrode positions.

Next, for each time window, follow-up repeated-measure ANOVAs with the factors Condition, Learning Status, Region and Laterality were performed. In the first time window (150–220 ms), there was a main effect of condition [$F(1,23)=7.41$, $p=.012$], reflecting the enhanced P2 for Think than No-Think trials.

In the following three consecutive time windows, significant Condition × Region × Laterality interactions emerged [350–450 ms: $F(4,92)=5.81$, $p=.001$, $\varepsilon=.69$; 450–600 ms: $F(4,92)=8.45$, $p=.0001$, $\varepsilon=.69$; 700–900 ms: $F(4,92)=5.18$, $p=.003$, $\varepsilon=.70$], indicating that within each time window both conditions differ across the factors Region and Laterality. In addition, in the 700 to 900 ms time window, there was a main effect of Learning Status, $F(1,23)=6.11$, $p<.02$. Trials from the learned condition elicited more positive going ERPs than non-learned trials.

In the 350–450 ms time window, follow up analyses revealed more negative going waveforms in the No-Think

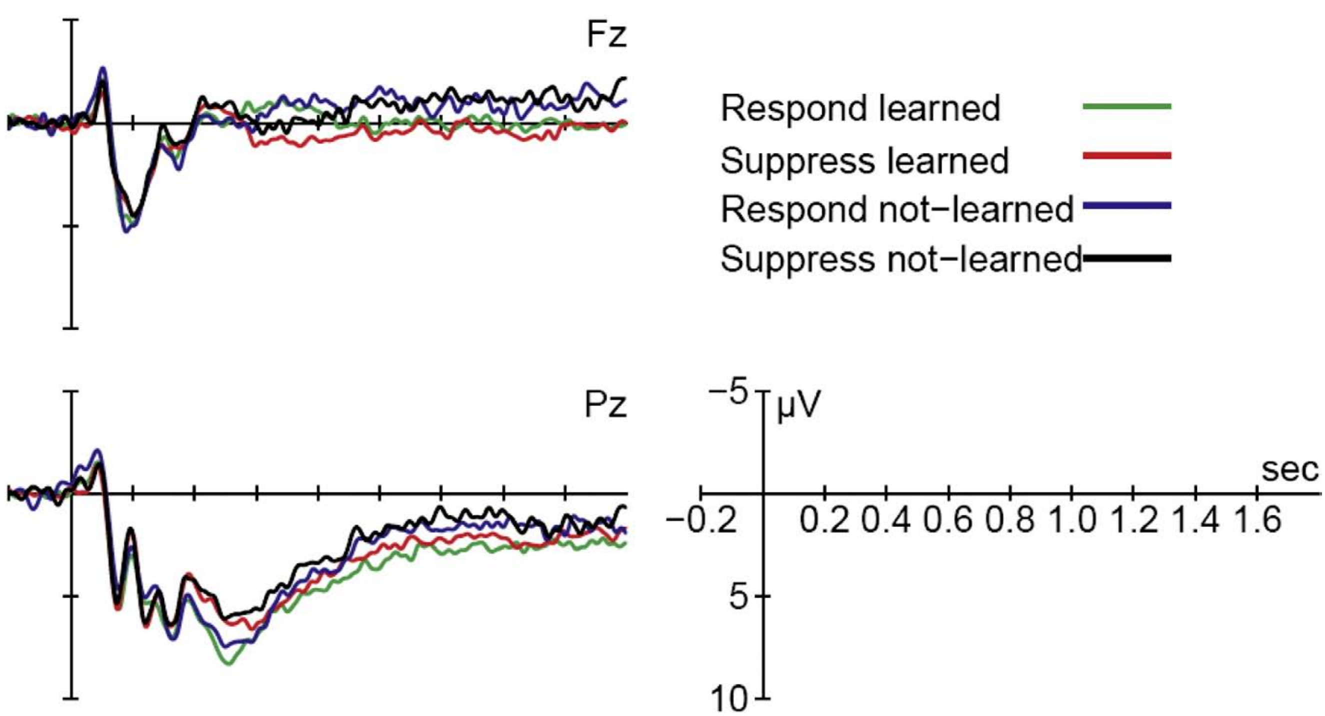

Fig. 3 – Grand average ERP for the Think and No-Think condition separated on the basis of prior learning success or failure. The waveforms are shown for the Fz and Pz recording site.

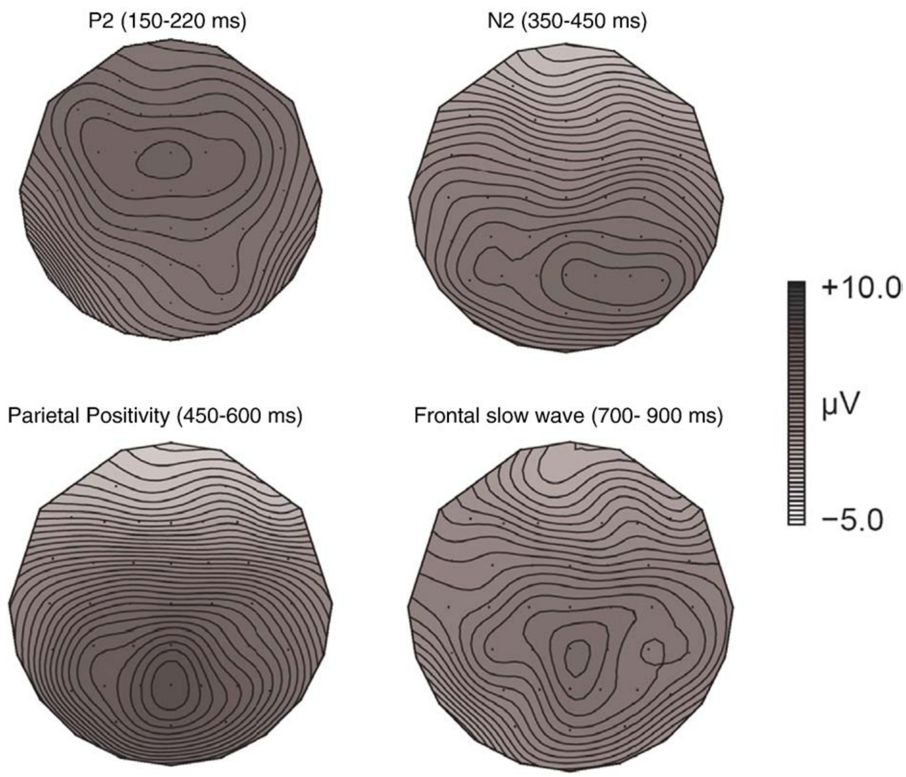

Fig. 4 – Scalp potential maps of the four effects found in the Think/No-Think phase: The P2, the N2, the parietal positivity and the frontal slow wave. The scalp topographies are plotted for the response condition in which the effects was largest, i.e. the P2 and the parietal positivity to Think trials and the N2 and frontal slow wave to No-Think trials.

condition than in the Think condition at parietal locations [left: $F(1,23)=7.31$, $p=.01$; middle: $F(1,23)=6.68$, $p=.01$; right: $F(1,23)=10.56$, $p=.003$]. In the 450–600 ms time window, a Think>No-Think pattern was obtained at all parietal [left: $F(1,23)=19.52$, $p=.0002$; middle: $F(1,23)=19.34$, $p=.0002$; right: $F(1,23)=16.46$, $p=.0003$] and central recording sites [left: $F(1,23)=7.06$, $p=.01$; middle: $F(1,23)=9.98$, $p=.004$; right: $F(1,23)=8.18$, $p<.009$]. In the 700–900 ms time window a reversed pattern was obtained at frontal recording sites: The ERPs in the No-Think condition were more positive than in the Think condition [left: $F(1,23)=9.19$, $p=.006$; middle: $F(1,23)=7.49$, $p=.01$; right: $F(1,23)=5.34$, $p=.03$]. Additionally, at the left parietal side the Think>No-Think pattern, observed in the two preceding time windows was also present in the 700 to 900 time interval. [$F(1,23)=15.77$, $p=.0006$].

As a Think>No-Think pattern was found in the 350 to 450 ms and the 450–600 ms time windows with a similar centro-parietal distribution, an important issue to be addressed whether these two effect differ in their topographical distribution and, by this, reflect qualitatively different processes arising from different neural generators (Rugg and Coles, 1995). Alternatively they could reflect activity from the same neural source extended in time. Topographical profile analyses were performed on the rescaled differences measures between both conditions in both time windows. The 24 scalp electrode sites that were used for this analysis were pooled on the Region (8 levels) and Laterality (3 levels) dimensions. This analysis revealed a reliable interaction between Window, Region and Laterality [$F(14,322)=5.33$, $p=.0002$)]. Follow up analyses revealed larger Think /No-Think differences in the second (450–600 ms) than in the first (350–450 ms) time interval at fronto-polar (Fp1, Fpz, Fp2), frontal (F4) and parietal (P3) recordings (all p-values<.02) This suggests that different brain systems contribute to the Think/No-Think differences in both intervals.

As apparent from Fig. 2 and 3, starting at around 700 ms the ERPs to learned trials were more positive going than to not-learned trials, irrespective of the attempts to retrieve (Think condition) or to avoid retrieval (No-Think condition). This effect is broadly distributed across the scalp and was statistically confirmed by a main effect of Learning Status in the 700 to 900 ms time interval. To further follow up this effect we conducted a four-way ANOVA for the 900 to 1100 ms time period. A main effect of Learning Status ($F1,23)=16.23$, $p<.001$, suggests that additional processing for learned materials that is not affected by attempts to retrieve or to avoid retrieval takes place even in this late time interval.

Interestingly, no interactions between Learning Status and Response condition were found in neither time interval. In other words, all effects of Response Condition were obtained irrespective of whether the target was retrievable (as for learned materials) or not. We therefore suggest that our findings in the Think/No-Think phase reflect four effects associated with the strategic control of memory retrieval. Retrieval attempts are associated with an enhanced P2 component and an enhanced parietal positivity between 450 and 600 ms, that extended in the 700 to 900 ms time interval at the left parietal recording site. Conversely, attempts to avoid retrieval are characterized by an enhanced N2 component, that resembles N2 components usually obtained in motor stopping paradigms. In addition a late and frontally focused positivity between 700 and 900 ms was obtained, that was larger for No-Think than for Think trials.

An important issue concerns item specific control processes. Following the logic of Bergström et al (2007), we assumed that successful avoidance of retrieval should be evident by two patterns of results: First the parietal positivity should be attenuated in learned No-Think relative to learned Think trials. Second, if retrieval avoidance is completely successful, the parietal positivity to learned No-Think trials should not only be attenuated (as compared to learned Think trials) but also indistinguishable from those to not-learned trials in which retrieval is not possible. We tested these two predictions by comparing the relevant conditions in the 450 to 600 ms time window at the mid parietal recording site, where the parietal positivity was largest. It was larger for learned Think than for learned No-Think trials, $F(1,23)=15.87$, $p=.0006$. It was also not different for not-learned No-Think and learned No-Think trials, F-values <1. However, not-learned Think trials elicited a larger parietal positivity than learned No-Think trials, $F(1,23)=4.29$, $p<.05$.

2.2. Discussion

This pattern of results implies that the parietal positivity is sensitive to retrieval avoidance for items that are in principle retrievable. However, the larger positivity for not-learned Think trials than learned No-Think trials suggests that beside item specific retrieval, the parietal positivity is also sensitive to retrieval attempts even in situations in which these attempts are not successful, as for not-learned materials. In finding no interaction between learning status and response condition, our results are in contrast to those of Bergström et al (2007). The main difference between the results of both studies was that the parietal positivity was modulated by mere retrieval attempts even for not learned materials in the present but not in the former study. While the retrieval attempt effect in our study had the same temporal characteristics as the No-Think effect for learned materials, this effect was smaller and restricted to a later time-window in the Bergström et al (2007) study. This may suggest that our subjects engaged more in retrieval attempts upon presentation of the retrieval cues even for not learned materials. Even though both studies were highly similar with respect to study materials, and experimental set up, they differed in the criterion for initial learning and the presence of feedback in the relearning phase. The learning criterion was 25% in the Bergström et al (2007) study and 66% in the present study and test words not recalled were represented during relearning in our study but not in the former study. As our participants in turn spend longer for relearning and received feedback on not learned materials, it is conceivable that there was a spill over from the preceding relearning phase, by which subjects tried harder to retrieve words that were not learned in the initial learning phase. This in turn may have lead to the correct retrieval of some of these words, even though they were not learned in the initial study phase. Indirect support for the latter view can be derived from the comparison of memory performance in the subsequent SP recall test. While performance was comparable across studies for the baseline and No-Think condition, the percentage of recalled items after the Think condition was slightly larger (96%) in the present study as in the Bergström et al. study (92%).

Attempts to avoid retrieval elicited a centro-parietal N2 with a peak latency of about 400 ms. As it preceded the attenuated parietal positivity, it might reflect a neural signal that initiates the inhibitory control of memory retrieval. A further hint towards the functional significance of the N2 can be derived from the task instructions in the Think/No-Think phase: While in the test-feedback cycles preceding the Think/No-Think phase the subjects had to answer aloud with the appropriate response word, during the Think/No-Think trials they either had to silently think of the correct response word, or to suppress the response word and avoid any thought about it. By this, both conditions required the avoidance of an overt response and it is reasonable to assume that the N2 to Think and No-Think trials reflects these general motor stopping requirements in both conditions. From this it follows that the larger N2 to No-Think than to Think trials may indeed reflect the additional attempts to avoid retrieval.

To further explore this issue a subsequent forgetting analysis was performed. We assumed that if the N2 to No-Think trials is related to attempts to avoid retrieval it should be larger to those cue words for which the target words were forgotten in the subsequent cued recall test than to those that were subsequently remembered. The subsequent forgetting status was derived from the Independent Probe Test, as memory performance in the Same Probe Test was too good, so that not enough forgotten trials were available. As the N2 in the No-Think condition was not modulated by prior learning status, the subsequent forgetting analysis was performed for all trial in this condition, i.e. irrespective of learning status.

The ERP waveforms elicited in the No-Think condition for subsequently forgotten and remembered words are illustrated in Fig. 5. As apparent from the figure the N2 in the No-Think condition was larger for subsequently forgotten words than remembered words. This effect was slightly more extended in time than the N2 effect of Response condition (cf. Fig. 2) and shows a midline central scalp topography. An ANOVA with factors Memory Status (forgotten vs. remembered), Region (frontal, central, parietal) was performed for the mean amplitude measures in the 350–480 ms time interval at the three midline recordings at which this subsequent forgetting effect was most pronounced. This analysis revealed a Memory Status × Region interaction, [$F(2, 46)=6.56$, $p<.003$, $\varepsilon=.98$]. Follow up analyses revealed larger N2 components for subsequently forgotten words at Cz and Pz (p-values<.05). This result confirms the view that the N2 to No-Think trials reflects neural activity related to retrieval avoidance.

3. Experiment 2

It has repeatedly been proposed that parallels exists between inhibitory control of memory and of stopping prepotent motor responses. Both situations are characterized by a respond override requirement in that the activation of a prepotent

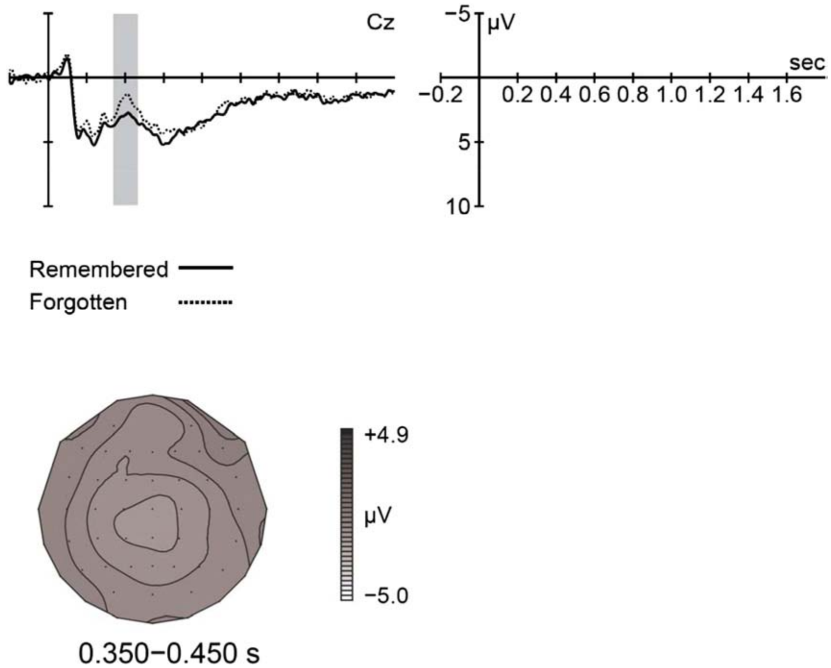

Fig. 5 – Grand average ERPs at Cz in the No-Think condition elicited by words which were forgotten and remembered in the subsequent Independent Probe Test. The scalp topography of the difference between subsequently remembered and forgotten trials in the 350 to 450 ms range is illustrated in the lower part of the figure.

response has to be suppressed in favour of a weaker but contextually appropriate response (Anderson, 2005). It is conceivable that general control mechanisms are recruited to inhibit the spread of activation to a motor response and the activation of a memory-stored item by an appropriate retrieval cue. The observation that attempts to suppress memory retrieval elicit a N2 component with similar characteristics as observed for N2 components in motor stopping tasks can be taken as a first hint towards general control mechanisms, being recruited to suppress external and internal actions. To further explore the extent to which the N2 to No-think trials reflects domain general control mechanisms, a second experiment was conducted, employing a stop signal task (SST). In this experiment the subjects were the same as in the Think/No-Think study and the same words that served as cue words in the aforementioned study were used. Rather than the suppression of memory retrieval this experiment required the suppression of a prepotent motor response upon presentation of a stop signal. If the same response override mechanisms are recruited to suppress memory retrieval and prepotent motor responses we expected the ERP indices of motor stopping to be correlated with the N2 in the Think/No-Think phase.

In a SST, subjects are presented with a series of trials, on each of which they perform a two-choice reaction time task. On some trials, an unpredictable stop signal follows the stimulus by a variable interval and the subjects are required to withhold their response on that trial. As the subjects have to be prepared to withdraw their response on each trial, the SST is a direct task to measure inhibitory control and shares important characteristics with the Think/No-Think procedure in which No-Think cues are also unpredictable. For shorter stop signal intervals it is easier to inhibit responding, whereas for longer stop signal intervals (400 to 600 ms) stopping is more difficult and by this, occurs less frequently (Schmajuk et al., 2006). The stop signal reaction time is a measure of the reaction to the stop signal at any given stop signal delay. As it cannot be measured directly it is calculated by subtracting the stop signal delay from the RT in Go trials (van Boxtel et al., 2001).

Recent ERP studies employing the SST found an N2 followed by a centrally distributed P3. Both components were found to be enhanced for successful as compared to unsuccessful stop trials (Schmajuk et al., 2006, Liotti et al., 2005; but see Kok et al., 2004) and it was proposed that the stop signal N2 may reflect the successful initiation of the inhibitory control process, whereas the P3 may reflect the evaluation of the outcome of this process (Liotti et al., 2005). Accordingly, we expected successful stopping to be correlated with enhanced N2 and P3 to stop signals.

3.1. *Results*

3.1.1. *Behavioral data*

Task performance was fast and accurate. Mean response time in Go trials was 511 ms (SD=62) and Go errors amounted to 0.23% (SD=0.30). The SSRT was 332 ms (SD=55) and by this slightly longer than SSRT found in other SST with easier two-choice reaction time tasks (e.g. van Boxtel et al., 2001; Schmajuk et al., 2006). The Stop signal errors amounted to 53% (SD=3.4) and by this approached the 50% ratio intended by the stepwise tracking procedure.

3.1.2. *ERP data*

Grand average ERPs elicited by successful stop trials (SST) and unsuccessful stop trials (USST) at three midline recordings are illustrated in Fig. 6. As apparent from the figure successful stopping was associated with an enhanced N2 with a parietal

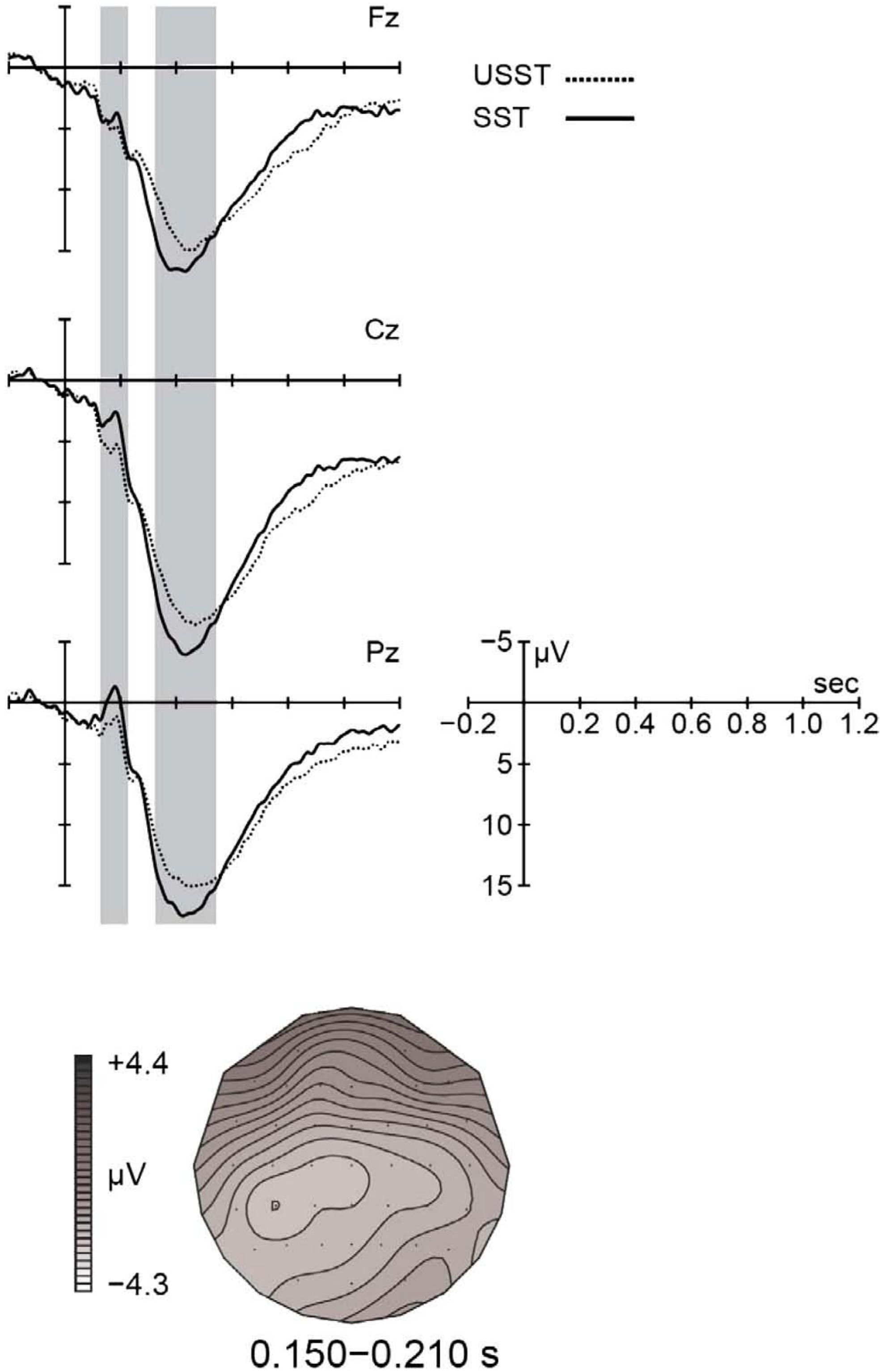

Fig. 6 – Grand average ERP elicited by successful and unsuccessful stop signal trials in the Stop Signal task of Experiment 2. The waveforms are shown for the three midline electrodes, Fz, Cz and Pz and the scalp topography of the difference between successful and unsuccessful stop signal trials in the 15β to 210 ms range is illustrated in the right part of the figure.

maximum that was followed by a P3 with a more centrally focused scalp topography. An ANOVA with the factors Condition (SST, USST), Time Window (150–210 ms, 350–550 ms), Region (frontal, central, parietal) and Laterality (left, middle, right) yielded a significant four-way interaction [$F(4,84)=3.24$, $p=.0276$, $\varepsilon=.75$], indicating that the N2 and P3 to successful and unsuccessful stop trials varied across the time windows and across the electrodes positions.

For each time window, follow-up ANOVAs with Condition, Region and Laterality as factors were performed. In the N2 time window (150–210 ms) there was a main effect of Condition [$F(1,21)=14.16$, $p=.0011$] that was embedded in a Condition × Region interaction [$F(2,42)=11.93$, $p=.0005$]. Post hoc contrasts indicated that the N2 was larger for SST than USST at central and parietal regions (p-values $<.05$), but not at frontal regions $p>.10$. In the P3 time interval a main effect of Condition [$F(1,21)=19.55$, $p=.0002$] was obtained, that reflects the broadly distributed enhanced P3 to successful Stop trials. Notably, the centro-parietal scalp topography of the difference between SST and USST (cf. Fig. 6) is similar to the scalp topography of the N2 to No-Think trials in Experiment 1 (cf. Fig. 4), albeit slightly more left lateralized.

3.1.3. Correlation analyses

A final set of analyses was performed to examine whether the ERP responses to attempts to avoid retrieval (Experiment 1) and to successful stopping (Experiment 2) are correlated. We assumed that if the same response override mechanisms are recruited to suppress memory retrieval and prepotent motor responses, the ERP indices of successful motor stopping to be correlated with the proportion of the N2 related to retrieval avoidance (N2 No-Think – N2 Think). As illustrated in Fig. 7, the N2 effect in Experiment 1 (N2 No-Think – N2 Think) was positively correlated with the N2 effect in the SST (N2 SST – N2 USST), $r=.41$, $p<.05$. The corresponding correlation between the N2 effect in Experiment 1 and the P3 effect in the SST did not reach the significance level. $r=.25$. The ERP indices of successful motor stopping (N2 SST – N2 USST) and successful retrieval avoidance (N2 No-Think subsequently forgotten vs subsequently remembered) were not correlated, $r=-.005$. All measures of the correlation analyses were taken from the Cz recording site.

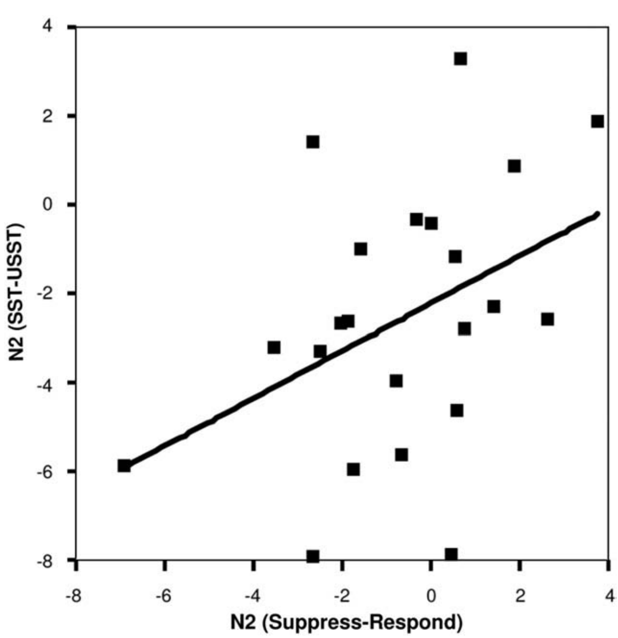

Fig. 7 – The positive correlation between the N2 effect in Experiment 1 (N2 No-Think – N2 Think) and the N2 effect in the SST in Experiment 2 (N2 SST – N2 USST).

3.2. Discussion

This experiment examined ERP correlates of the inhibitory control of prepotent motor responses. Participants performed a Stop Signal Task, that requires to withdraw a motor response on some trials. Consistent with other ERP studies, successful stopping was associated with enhanced N2 and P3 components. Given its early peak at 182 ms (Cz) it can be assumed that the N2 reflects an early mechanisms of inhibitory control, i.e. the successful initiation of the inhibitory process. Conversely, the stop signal P3 may reflect processes that act downstream of the inhibition process, the monitoring or evaluation of the outcome of successful inhibition (Liotti et al., 2005).

The main goal of Experiment 2 was to explore if the same response override mechanisms are recruited to inhibit motor responses and to suppress memory retrieval. To approach this issue, we tried to equate the testing procedures between motor inhibition and memory suppression by recruiting the same participants and by using the same stimulus materials as in Experiment 1. A selective positive correlation was found between the No-Think–Think N2 effect in Experiment 1 and the Stop Signal N2 in Experiment 2. This suggests that the initiation of attempts to suppress unwanted memories (as reflected in the No-Think N2) and the initiation of successful motor stopping share common variance.

Another ERP effect of Experiment 1 that is relevant for comparison with the ERP correlate of successful motor stopping is the subsequent forgetting effect illustrated in Fig. 5. Both effects can be assumed to reflect neural activity related to the successful suppression of a response. However, as no correlation was found between both measures it is reasonable to assume that additional control processes were recruited in the service of successful stopping of memory retrieval that were not relevant for successful motor stopping.

Our result suggests that the initiation of attempts to suppress unwanted memories (as reflected in the No-Think N2) and the initiation of successful motor stopping are functionally related. By this, they support the view that highly similar response override mechanisms are recruited to suppress memory retrieval and prepotent motor responses.

4. General discussion

This study addressed two main issues: One goal was to elucidate the neurocognitive processes mediating attempts to retrieve or to avoid retrieval of previously learned word pairs on the one side and the outcome of these strategic and voluntary processes, namely successful retrieval or avoidance of retrieval on the other side. The second goal was to examine whether the control of internal actions (i.e. memory retrieval) and the control of external actions (i.e. stopping prepotent motor responses) have similar ERP correlates.

In Experiment 1, ERPs were analysed in the No-Think and Think conditions of an intentional forgetting paradigm (Anderson and Green, 2001). For the ERP analyses the Think and No-Think trials were separated on the basis of prior learning failure and success. The assumption was that strategic effects of memory control should be reflected in the ERP irrespective of prior learning success, whereas item-specific effects, i.e. ERP correlates of successful retrieval or retrieval avoidance should be obtained for successfully learned items, for which item-specific memories exist, so that they are in principle retrievable (see Bergström et al., 2007 for a similar approach).

On the behavioural level, the general finding from Anderson and Green (2001), a decline in the cued recall of No-Think items relative to the baseline condition could not be replicated in the present study. A follow up analysis revealed that the semantic relatedness between the cue and response words cannot account for the absence of suppression effects. Consistent with other studies reporting failures to find suppression effects (Bulevich et al., 2006; Bergstöm et al., 2007) we assume that these effects are small and not always replicable, even when the experimental procedures are closely matched with those of the initial study by Anderson and Green (2001). As suggested by Hertel and Calcaterra (2005), retroactive interference by substitution may be an important mechanism for behavioural suppression effects to occur. They showed that a strategy in which participants, upon presentation of a No-Think cue, substitute one response word by another, leads to later forgetting, whereas other subjects not using such a substitution strategy did not show effects of suppression on a later explicit memory test. Furthermore, as suggested by Levy and Anderson (2002), Hertel and Gerstle (2003), individual differences in memory strategies might influence the effectiveness of suppression. Nonetheless, in the present context, even though no behavioural forgetting effects were obtained, the ERP analysis of the Think/No-Think phase can still reveal important insights in the mechanism by which memory retrieval can be avoided, event though this retrieval avoidance not necessarily has to lead to enhanced forgetting in the following cued recall test.

4.1. *The strategic control of memory retrieval*

Our ERP analysis of the No-Think and Think condition revealed a pattern of four effects related to the strategic control of memory retrieval. Retrieval attempts are associated with increased P2 amplitudes. In fact, when subjects are cued to retrieve a member of a word pair (Think condition) by the green-coloured cue words, the P2 is larger than in the No-Think condition. Positive ERP components with frontal or fronto-central scalp topographies in this latency range are typically found in tasks in which attention has to be allocated to visual features of an event. For example the P2 effect in the present study resembles the frontal selection positivity (Smid et al., 1999) that is typically observed when subjects attend to visual features or feature conjunctions. Consistent with these findings we assume that the P2 effect in the present study, presumably reflects the higher amount of attention allocated to the colour-coded cue words in the Think condition, In support of this view, Bergström et al (2007) report a similar positivity between 200 and 300 ms in the Think/No-Think phase of an intentional forgetting experiment, being larger in the Think than in the No-Think condition, irrespective of whether the words have been learned before or not. On the basis of its temporal and functional characteristics, we assume that, rather than directly reflecting processes relevant for the control of memory retrieval, the P2 effect indexes enhanced selective attention triggered by the task-relevant stimulus attribute (colour) that precedes the engagement of control processes.

A second effect related to retrieval attempts was an amplitude increase of the parietal positivity that extended from 450 to 600 ms. As for the P2 effect this effect was found to be independent of the learning status in the prior study phase. Similar parietal positivities are typically obtained in recognition memory tasks and are thought to index recollection (Friedman and Johnson, 2000, Mecklinger, 2000; Curran et al., 2006). Our finding suggest that beside successful recollection, the parietal positivity is also sensitive to mere attempts to retrieve an item even when these attempts are not successful as for items that had not been learned. The sensitivity of the parietal positivity to retrieval attempts is in contrast to the findings of Bergström et al. (2007), where ERP correlates of retrieval attempts were smaller and also delayed in time. As outlined in the discussion of Experiment 1, the apparent differences in the results of both studies can be accounted for by assuming that the participants in the present study – presumably due to differences in the preceding relearning phase – spend more effort in the retrieval of unlearned materials.

ERP effects related to attempts to avoid unwanted memories were smaller and also restricted to a smaller time window. They took the form of a negativity with a centro-parietal distribution that peaked around 400 ms. This negativity was enhanced in No-Think relative to Think trials and bears similarities to N2 components related to stopping prepotent motor responses, as typically observed in Go-NoGo or Stopping tasks (Garavan et al., 2002; Kok et al., 2004; Schmajuk et al., 2006). As revealed by a subsequent forgetting analysis, this negativity to No-Think trials was larger when the words were indeed forgotten in the final recall test. These functional characteristics of the N2 to No-think trials suggest that, in addition to general motor stopping requirements it also reflects neural process that successfully initiate the avoidance of retrieval attempts.

A final effect related to the strategic control of memory retrieval was a frontally focused positivity between 700 and 900 ms. Given its rather late onset and frontal scalp distribution this positivity presumably reflects more general aspects of control of memory retrieval. A hint towards the functional significance of this effect can be derived from a recent ERP study on retrieval induced forgetting (Johansson et al., 2007). In this paradigm no instruction to forget is given and forgetting is rather a by product of retrieving other materials from memory. Johansson et al. (2007) found that a frontal positivity elicited by previously learned words that had to be retrieved a second time in a retrieval practice phase, to be correlated with the amount of forgetting of not practiced materials. This suggests that the frontal positivity may be engaged in the control of competing memory traces by suppressing currently irrelevant traces (not practiced materials) in favour of task relevant ones (to be practiced materials). In the present study it could reflect similar control mechanisms to regulate competing memory traces in order to prevent unwanted memories. Given its frontal scalp distribution it is reasonable to assume that the frontal positivity arises from PFC structures, that are recruited by this form of cognitive control in a variety of tasks (Shimamura, 2000).

Starting at around 700 ms previously learned words elicited positive slow activity that extended for several hundred ms and was broadly distributed over the scalp. In other words: Irrespective of voluntary attempts to retrieve or avoid retrieval, cue words that refer to previously learned word pairs elicited more positive going ERP waveforms than cues for which no corresponding word could be retrieved. It is conceivable that the presentation of retrieval cues has constituted a kind of re-encoding situation and that this late positivity reflects the delayed but successful retrieval of previously leaned word pairs. The late onset of this effects and its insensitivity to the Think/No-Think instruction suggests that the processes reflected by this positivity operate downstream and independent of the strategic mechanism required for memory control.

4.2. *Stopping memory retrieval and motor stopping*

The second issue addressed in the present study concerns similarities and differences in the control of actions and memory processes. Stopping of a motor response and stopping of memory retrieval can be characterized as a response override situation in which the activation level of a prepotent response has to be reduced in order to emit a weaker but contextually appropriate response (Anderson 2005; Anderson et al., 1994). We approached this issue by conducting a stop signal experiment with the same participants and testing materials and by examining similarities between the ERP correlates of successful motor stopping and of avoiding memory retrieval. Consistent with a variety of previous ERP studies on the control of motor behaviour using the stop signal paradigm (Schmajuk et al., 2006; Liotti et al., 2005), we obtained enhanced N2 und P3 components to successful as compared to unsuccessful stop trials. Even though the stopping N2 peaked about 200 ms earlier than the N2 elicited by No-Think trials in the memory study, both components had a similar centro-parietal scalp topography and showed a significant positive correlation. As no reliable correlation was obtained between the N2 to No-Think trials and the P3 to Stop trials we assume that the aforementioned correlation is not just a reflection of high within-subject covariance of ERP components but rather reflects the fact that similar neural systems are recruited by the initiation of attempts to suppress unwanted memories and the initiation of successful motor stopping.

In further support of this view, the scalp topographies of the ERP effects related to successful motor stopping (SST vs USST) and the N2 to No-Think trials as illustrated in Figs. 6 and Fig. 4, respectively show a similar centro-parietal distribution This topographic distribution is consistent with recent brain imaging (Garavan et al., 2002) and ERP source localisation studies (Nieuwenhuis et al., 2003) showing that successful stopping is mediated by medial frontal and parietal brain regions.

Other ERP studies on motor stopping with children and adults, however, revealed a right-frontally distributed N2 to successful stop trials (Schmajuk et al., 2006; Pliszka et al., 2000), suggesting that the right PFC additionally contributes to motor stopping. Even though the present ERP study does not allow strong inferences on the brain systems involved in the control of actions and memory retrieval, the centro-parietal rather than right frontal, scalp distribution of the ERP correlates of successful motor stopping and attempts to avoid retrieval may suggest that PFC structures are less engaged by motor stopping in the present study as compared to the aforementioned studies.

To illustrate this view, it is helpful to consider the temporal characteristics of the ERP components associated with successful stopping in both tasks. The relative timing of the motor N2 and the No-Think N2 with peak latencies at 182 ms and 402 ms, respectively, suggests that they reflect early mechanisms of control, namely the initiation of the inhibitory process. A recent study with combined fMRI and ERP recordings (Garavan et al., 2002) revealed that medial frontal regions (i.e. the anterior cingulate) and the (right) dorsolateral PFC differently contribute to inhibition under conditions of fast and slow ongoing response speed, respectively. The dorsolateral PFC was more engaged in task situations in which ongoing response speed was low and motor stopping was relatively difficult, whereas the anterior cingulate was stronger recruited when ongoing response speed was high. Though speculative, the common variance of the stop signal N2 and the N2 to No-Think trials and their similar centro-parietal scalp topographies may reflect the recruitment of the anterior cingulate for the initiation of motor and memory stopping. Further control processes as the regulation of competing memory traces might have been additionally required in the more difficult retrieval avoidance situation and the late frontal positivity to No-Think trials may reflect the additional recruitment of PFC structures for these enhanced control demands in the Think/No-Think phase.

5. Conclusions and open issues

In conclusion, the present study provides further evidence of the view that the ERP correlates of strategic memory control, namely attempts to retrieve or to avoid retrieval and the outcome of these processes, namely successful retrieval and retrieval avoidance can be dissociated. We found four ERP effects related to the strategic control of memory retrieval: An early P2 component, and a parietal positivity, related to retrieval attempts and a centro-parietal N2 component associated with attempts of retrieval avoidance. An additional late frontal slow wave presumably reflects more general aspects of cognitive control, i.e. the control of competing memory traces. The parietal positivity was attenuated to learned No-Think trials for which item-specific memories exist and memory retrieval is in principle possible. However, under the present testing condition the parietal positivity was also sensitive to mere retrieval attempts. Retrieval processes for learned materials, as reflected in a broadly distributed positive slow wave, was apparent after 700 ms, suggesting that these processes are automatically initiated by the cues and not under voluntary control. Importantly, the ERP correlates of successful retrieval avoidance were obtained without behavioural effects of forgetting in the later cued recall tests and further studies will be required to examine the conditions under which retrieval avoidance results in forgetting below baseline level.

Finally, even though both processes differ in their temporal characteristics a significant correlation was obtained between the ERP correlates of the initiation of motor inhibition and the suppression of memory retrieval. By this the present study provides further evidence for the view that some of the systems recruited to override prepotent motor responses are also involved to suppress memory retrieval.

6. Experimental procedures

6.1. Experiment 1

6.1.1. Subjects

A total of 24 healthy native German speakers from Saarland University (12 female between 20–26 years of age, mean age 23.4 years) participated in this study. Subjects had normal or corrected-to-normal vision, including normal color vision. They all gave written informed consent before the experiment and received payment for participating. None of the subjects had any prior experience with the experimental task.

6.1.2. Stimuli

70 weakly related word pairs were composed, 60 of which functioned as critical items and 10 as filler items. Each word pair comprised a cue (left hand word) and a response (right hand word) word. Words were selected from a German standardized data base (Meier, 1967; Mannhaupt, 1983, Scheithe and Bäuml, 1995; Hager and Hasselhorn, 1994) on the basis of their frequency of occurrence in each category. From each category two members were selected and recombined so that each response member (right word) was the only member of each category, to permit later testing of that item with a correspondent category cue in the independent probe recall test (see below). The selection of the final experimental word pairs was guided by a rating procedure In this procedure words with orthographical and phonological similarities were excluded .and only pairs with weak semantic relationship were included. All word stimuli were presented using the E-Prime software in central vision on a 75 Hz computer screen on a white background.

6.1.3. Procedure

After subjects signed a written consent form and completed a questionnaire assessing general personality variables in the first session, the Think/No-Think experiment started, with an initial learning phase, the subsequent Think/No-Think phase and a final recall test phase.

The participants initially studied all 70 pairs, of which 20 pairs were assigned to the Think condition, 20 to the No-Think condition, and 20 the Baseline condition. Pairs of the Baseline condition were presented only in the learning phase and formed a behavioural baseline condition for the later final cued recall test (see below). The Think and No-Think word pairs were then included in the subsequent Think/No-Think phase (see below). All word pairs including the filler items (the remaining 10 pairs) were exposed for 5 s on a white background at the center of a computer screen, in randomized order, separated by a blank screen displayed for 1000 ms. Subjects were asked to silently memorize all word pairs as good as possible. The learning phase was followed by a relearning phase, in which subjects were instructed to answer loud with the appropriate response word as quickly as possible upon presentation of each cue word. The cue word was displayed for 2.5 s, accompanied by a dash and a question mark to the right of the cue. Every trial started with a blank screen shown for 1000 ms. The next trial was triggered as soon as the correct response word was recalled. In case of an incorrect recall of the response word within the 2 s time window, the correct response was shown at the position of the question mark. In this manner, the original word pair was displayed for 1 s again. After termination of a relearning phase, subjects received feedback in the form of their average total recall rate in the current phase If the recall rate of a relearning phase was less than 66%, the word pairs, that have been recalled incorrectly, were presented again to the participants. This was followed by a new relearning phase including all word pairs again. The relearning phases with all word pairs continued until the subjects reached the criterion of a minimum 66% of correct responses. If a subject failed to reach this criterion after 3 repetitions, the experiment was aborted.

In the subsequent Think/No-Think phase, subjects were given the Think/No-Think instructions. In this phase of the experiment, only the cue words were presented. In the Think trials the cue word was presented in green color and subjects were instructed to silently think of the correct response word. In the No-Think trials (red cue words), they were asked to suppress the response word and avoid any thought about it. Subjects were told to focus on the screen and actively suppress the response word. No overt responses were required in the Think/No-Think phase. After a brief practice on filler items, subjects were given 640 trials, with 320 Think and 320 No-Think trials on critical items. Each cue word for the Think as well as for the No-Think condition was presented 16 times. Think and No-Think stimuli were randomly intermixed. The stimuli remained on the screen for 3500 ms. Trials were separated by a 1000 ms intertrial interval. No-Think and Think trials were conducted on different word pairs.

In the final cued recall phase, subjects' memory for all of the word pairs was tested in two ways. In the Same Probe test (SP test), subjects were presented with the original cue word of the critical trials that was paired with the response word throughout the experiment. In the Independent Probe test (IP test), subjects were cued with the category name for each response word of the critical word pairs along with its first letter. All items were included in both, the SP and the IP test. In both cases, subjects were asked to recall the studied item that fit each cue. In contrast to the Think/No-Think phase, all words were printed in black colour in the centre of the screen for 4 s as in the learning phase of the experiment. Subjects were asked to respond with the first word coming to mind, but not before a question mark appeared on the screen for 2 s. Trials were separated by a blank screen for 1 s. Both recall tests were counterbalanced across subjects.

For the learning and the final recall test phase, the response accuracy was recorded by a key press from the experimenter. The ERPs reported here are from the Think/No-Think phase.

6.1.4. EEG-recording

Subjects were seated in an electrically shielded room. While performing the Think/No-Think phase and the final recall test phase, the electroencephalogram (EEG) was continuously recorded from 61 Ag/AgCl electrodes embedded in an elastic cap and labelled according to the extended 10–20 system. The ground electrode was AFz. The left mastoid served as reference for the EEG recordings from all sites. The electrodes were rereferenced off-line to the average of the left and right mastoids. Vertical and horizontal eye-movements were controlled with additionally electrodes placed above and below the right eye (VEOG) and outside the outer canthus of both eyes (HEOG). All channels were amplified with a band-pass from DC to 100 Hz and converted with 16 bit resolution at a sampling rate of 500 Hz. The inter-electrode impedances were kept below 5 kΩ. The continuous EEG data was off-line filtered with a digital low-pass filter set to 30 Hz. Epoch duration used for analyses was 2000 ms, including a 200 ms pre-stimulus period used for baseline correction. Trials containing muscle and/or recording artefacts were rejected, and trials with ocular artefacts were corrected prior to averaging using a linear regression approach (with a minimum of 15 artefact-free trials per condition and participant). ERP averages were formed for the two conditions (Respond/Suppression) in the Think/No-Think phase separately for trials that were successfully learned or not learned in the study phase and were time locked to the onset of the cue word in both conditions. The mean trial numbers were 97 (learned Think condition), 40 (not-learned Think condition), 94 (learned No-Think condition) and 45 (not-learned No-Think condition).

6.1.5. Data analyses

Behavioral and ERP data were analyzed using repeated measures analyses of variance (ANOVAs) with an alpha level of .05. The Greenhouse–Geisser correction for non-sphericity was used whenever appropriate and epsilon-corrected p values are reported together with uncorrected degrees of freedom. Statistical analyses of behavioural data were conducted from the responses of the final recall test phase.

ERP waveforms in the Think/No-Think phase of the experiment were quantified by measuring the mean amplitudes in four time windows (150–220, 350–450, 450–600, 700–900 ms) for the overall data. Selection of the time windows for ERP analyses was based on a visual inspection of the waveforms and aimed at tapping the differences between the Think and No-Think conditions. Statistical analyses of the ERP data was based on the following scalp electrodes: frontal (F3, Fz, F4), central (C3, Cz, C4) and parietal (P3, Pz, P4). For topographical analyses data from 24 electrodes at midline sites (Fpz, Fz, Fcz, Cz, Pz, POz Oz) and the corresponding lateral sites (Fp1/2, F3/4, FC3/4, C3/4, CP3/4, P3/4 PO3/4, O1/2) were taken into account and were normalized using the vector scaling procedure as described by McCarthy and Wood (1985) in order to eliminate any confounding effects of differences in magnitude.

Scalp potential maps were generated using a two-dimensional spherical spline interpolation and a radial projection from Cz, which respects the length of the median arcs.

6.2. Experiment 2

6.2.1. Subjects

The subjects were the same as in the Think/No-Think experiment. As two of them could not participate in a second study, the sample consisted of 22 subjects (10 female; mean age was 23.4 years, ranging in age from 20 to 26 years). The interval between both experiments was more than a year and all participants reported that they did not remember any word from the Think/No-Think task. They all gave written informed consent to participate in the study and received payment for participating. None of the subjects had any prior experience with the experimental task.

6.2.2. Stimuli and procedure

Participants performed the SST and a standard Go–NoGo task in which subjects made two choice responses (Go trials) or had to withdraw their responses on a subset of trials (NoGo trials). Task order was counterbalanced across subjects and had no effect on the behavioural and ERP variables analysed in the SST. As the results of the Go–NoGo task will be reported elsewhere only the procedure of the SST will be described in the following:

The cue words from the Think/No-Think task were used as stimuli. The stimuli were presented in black against a white background in the center of a 75 Hz computer display. Participants performed a two-choice RT task in which they made an animacy judgment on each word. Each word was surrounded by a rectangular frame and the color of the frame served as visual cue that was used as the stop signal. The Go trials were indicated with a gray frame, in which subjects made animacy judgments by pressing a button with the index finger of the left or right hand. A change to a blue frame indicated that subjects should continue with a response (Go trials with color change). A color change to yellow indicated that the subjects should stop executing a response (Stop trials). The assignment of color cues for Go trials with color change and stop trials and the mapping of hands to the reaction stimuli was counterbalanced across subjects. The stop-signal task included a practice phase and an experimental phase. In the practice phase participants were familiarized with the animacy judgments. It consisted of a block of 24 Go trials without color change.

The experimental phases were administered in seven blocks of 120 trials each. The first block served as practice block and to adjust the accuracy level of response inhibition to approximately 50% (see stepwise tracking procedure below) and was excluded from data analysis. Each block consisted of 72 Go trials without color change (60%), 24 Go trials with color change (20%), and 24 Stop trials (20%) Each trial began with a 500 ms fixation cross. Thereafter the target was presented. It disappeared when the subject responded or after maximal target presentation (1250 ms). The next fixation cross appeared after 1000 ms. Within each block, the sequence of trials was pseudo-randomized with a maximum of three successive stop trials. The assignment of each word to each condition (Go60%, Go20%, Stop20%) was never repeated in successive trials.

The onset of the stop signal relative to the onset of the target stimulus (the stop signal delay (SSD) varied and was dynamically adjusted to the subjects' performance after each stop trial (e.g., Bedard et al., 2002; Logan et al., 1997) by means of a stepwise tracking procedure. The goal of this procedure was to allow participants to successfully stop on approximately 50% of the Stop trials. This is a precondition for the estimation of Stop Signal Reaction Time (SSRT), which is calculated by subtracting the mean SSD from the mean Go trials RT in Go trials without color change. The initial SSD was set to 250 ms at the beginning of the first block of the experimental phase. The initial SSD increased or decreased by 50 ms when subjects succeeded or failed to stop the response, respectively. The SSD at the beginning of each block was set to the SSD at the end of the preceding block.

All participants were informed about the rationale for the tracking procedure and received verbal and written instructions from the experimenter. They were instructed to react as quickly as possible and to maintain a high accuracy level. To prevent subjects from delaying their response in anticipation of the stop signal, at the end of each block, subjects received feedback about their mean RT in the Go trials. The experimenter explained to the subjects that it would not always be possible to stop a response upon appearance of a stop signal. Participants were also instructed to fixate the word on the screen and to avoid making eye or body movements when stimuli were presented. Task duration was 45 min for the SST and 10 min for the Go–NoGo task.

6.2.3. *EEG-recording*

The procedure for EEG and EOG recording and artefact handling was the same as in Experiment 1. ERP averages were formed for successful and unsuccessful Stop trials with a duration of 1400 ms, including a 200 ms pre-stimulus period used for baseline correction.

6.2.4. *Data analyses*

Performance measures included RT and error rate in the Go trials (GoRT and GoErrors) and the SSRT. ERP data were analyzed using repeated measures ANOVAs with an alpha level of .05. The Greenhouse–Geisser correction for nonsphericity was used whenever appropriate and epsilon-corrected p values are reported together with uncorrected degrees of freedom.

The mean trial numbers for the ERP analysis were 65 (SST) and 69 (USST). ERP waveforms of the SST and USST were quantified by measuring the mean amplitudes in two time windows (150–210, 350–550 ms) time-locked to the presentation of the stop signal, that reflect the N2 and P3 components, respectively, as reported in previous studies with the Stop-Signal Task (Kok et al., 2004; Ramautar et al., 2004; Schmajuk et al., 2006). Selection of the time windows for ERP analyses was based on a visual inspection of the waveforms. Statistical analyses of the ERP data was conducted with the same electrodes as in Experiment 1.

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