

Controlling Conflict from Interfering Long-term Memory Representations

Kerstin Jost^{1*}, Patrick H. Khader^{2*}, Peter Düsel²,
Franziska R. Richter³, Kristina B. Rohde⁴,
Siegfried Bien², and Frank Rösler⁵

Abstract

Remembering is more than an activation of a memory trace. As retrieval cues are often not uniquely related to one specific memory, cognitive control should come into play to guide selective memory retrieval by focusing on relevant while ignoring irrelevant information. Here, we investigated, by means of EEG and fMRI, how the memory system deals with retrieval interference arising when retrieval cues are associated with two material types (faces and spatial positions), but only one is task-relevant. The topography of slow EEG potentials and the fMRI BOLD signal in posterior storage areas indicated that in

such situations not only the relevant but also the irrelevant material becomes activated. This results in retrieval interference that triggers control processes mediated by the medial and lateral PFC, which are presumably involved in biasing target representations by boosting the task-relevant material. Moreover, memory-based conflict was found to be dissociable from response conflict that arises when the relevant and irrelevant materials imply different responses. The two types of conflict show different activations in the medial frontal cortex, supporting the claim of domain-specific prefrontal control systems. ■

INTRODUCTION

Recalling a specific entry from long-term memory (LTM) is a complex cognitive task. Specifically, remembering is more than an activation of a memory trace. Often, retrieval cues are not uniquely related to one specific memory entry. Therefore, control processes should come into play that help to flexibly search memory for behaviorally relevant memory representations while ignoring irrelevant ones. Processes that separate relevant from irrelevant information have been proposed for various attention tasks (Egner & Hirsch, 2005; Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005; Desimone & Duncan, 1995; Cohen, Dunbar, & McClelland, 1990). Here, we transfer these concepts and ideas to the memory domain and investigate how control processes manage the flexible allocation of attention to LTM representations. Moreover, we examined whether LTM-based conflict is processed similarly and activates the same brain processes as other types of conflict, such as response conflict.

Similar to the Stroop or the Simon task, in which a stimulus has two dimensions of which only one is currently relevant (e.g., when the task is to name the font color, the color word is irrelevant), participants in this study retrieved information from two stimulus classes, that is,

faces and spatial positions, of which only one was relevant in each trial. The retrieval of these stimuli classes has distinct neural correlates (e.g., Khader, Burke, Bien, Ranganath, & Rösler, 2005; Polyn, Natu, Cohen, & Norman, 2005; Ishai, Ungerleider, Martin, & Haxby, 2000; Moscovitch, Kapur, Köhler, & Houle, 1995), which allows investigating whether and to what degree irrelevant material becomes coactivated and interferes during retrieval. By directly modeling LTM interference after conflict occurring during “on-line” processing, this study contributes to bridging the gap between the domains of LTM and cognitive control.

It is commonly held that the PFC plays a major role in cognitive control (e.g., Koechlin, Ody, & Kouneiher, 2003; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Miller & Cohen, 2001). According to Miller and Cohen, task goals are maintained in PFC in the form of activation patterns that provide bias signals to other brain structures to guide the flow of information in many cognitive systems, such as visual processing and response execution. In principle, this should also hold for memory retrieval. Indeed, previous studies inducing conflict in LTM have found the ventrolateral PFC (VLPFC) to support controlled access to stored representations (e.g., Souza, Donohue, & Bunge, 2009; Kuhl, Kahn, Dudukovic, & Wagner, 2008; Nee, Jonides, & Berman, 2007; see Badre & Wagner, 2007, for a review). In addition, numerous studies using the think/no-think and retrieval-induced forgetting paradigms (e.g., Wimber et al., 2008; Anderson et al., 2004) suggest that prefrontal

¹RWTH Aachen University, ²Philipps-University Marburg, ³University of Oxford, ⁴University of Bern, ⁵University of Potsdam

*These authors contributed equally to the study.

activity is related to the inhibition of irrelevant semantic associations that might interfere with the retrieval of relevant ones during LTM retrieval. Consistent with these findings, Badre and Wagner (2007) concluded in their review that the PFC resolves interference between retrieved conceptual knowledge.

With this study, we want to extend this work. To delineate whether the same mechanisms are responsible for controlling conflict that occurs at different levels of cognitive processing, we compared LTM interference with another type of conflict: The present paradigm is also capable of inducing response conflict, that is, depending on whether relevant and irrelevant materials imply different responses. Thus, by inducing memory-based and response-related conflict, we are in the position to address the question whether different forms of interference resolution are carried out by a common prefrontal control system or by a set of different control functions that become recruited for specific control demands.

METHODS

Participants learned associations between words and visual stimuli, that is, faces and spatial positions. To ensure to capture LTM retrieval, the information was fully overlearned, and recall was tested at least 24 hr after learning. During retrieval, the stimuli had to be recalled with the words being the retrieval cues. Some of the words were linked only to faces or spatial positions, whereas others were linked to both, which led to retrieval interference. In each trial, two words were presented, and participants had to decide whether both were associated with the same stimulus. For this decision, only one material type was task relevant. For instance, participants were asked whether the two words were associated with the same face. Here, the position information was task-irrelevant. This paradigm allows for the investigation of the retrieval of different kinds of information while keeping the type of cue that triggers the retrieval constant. Depending on the type of word pair, three different conditions could be constructed (see Figure 1): Combining words associated with only one material type yielded a neutral control condition, in which only associations in the task-relevant dimension exist. Combining words that were associated both with a face and a position yielded two different conflict conditions, depending on whether the responses implicated by the material types were congruent or incongruent. For example, when two words are associated with the same position, but with different faces, this would be an incongruent condition. The incongruent condition contains material and response conflict, the congruent condition contains only material conflict, and the neutral condition does not contain any type of conflict. Accordingly, subtracting the neutral from the congruent condition yields the material conflict and subtracting the congruent from the incongruent condition yields the response conflict.

All in all, the two different types of conflict can be contrasted within the same task. In contrast to the more “classical” approaches of inducing interference in LTM retrieval, such as proactive and retroactive interference (e.g., Underwood, 1957) or retrieval-induced forgetting (Anderson, Bjork, & Bjork, 1994), conflict here arises between two different stimulus categories and, furthermore, is not based on the specific learning history of the associations.

During retrieval, we measured BOLD signals and ERPs from the same participants (albeit in separate sessions) to characterize the dynamics of processing and controlling interference during LTM retrieval. In previous studies, we found that retrieving faces and spatial positions of the same type as used here produced distinct fMRI activations (Khader et al., 2007; Khader, Burke, et al., 2005). This neural distinctiveness can be utilized to investigate whether not only relevant but also irrelevant material is being activated during retrieval. A similar rationale can also be applied to ERPs when slow waves are considered. These potentials are tonic ERP deflections that last for at least a couple of hundred milliseconds and have two important features: Their amplitude becomes more negative with increasing task difficulty or mental load and their topography is material- and task-specific (Rösler, Heil, & Röder, 1997). This material specificity in the EEG has already been shown for retrieving faces and spatial positions of the same type as used here (Khader, Heil, & Rösler, 2005; see also Mecklinger, 1998). Therefore, slow waves can be utilized to measure the retrieval of material-specific representations from LTM (see also, e.g., Heil, Rösler, & Hennighausen, 1996). The combination of the direct measure of neural activation via EEG with the precise localization provided by fMRI allows to “cross-validate” the found effects with different methods and to derive a coherent picture of the neural processes underlying interference during LTM retrieval.

Contrasting the two neutral conditions, that is, faces versus positions, should reveal ERP topographies and neural activations that can be regarded as indicators of material-specific LTM representations. Moreover, in the fMRI part, we also ran a functional localizer in which faces and positions were presented in a simple discrimination task. Theories about the role of the neocortex in storing LTM representations assume that stimulus representations are located in the cortical areas that are also involved in the perceptual processing of the information (e.g., O’Reilly & Rudy, 2001; McClelland, McNaughton, & O’Reilly, 1995; for reviews, see Danker & Anderson, 2010; Khader & Rösler, 2009). Therefore, functional localizers, in which the perceptual processing areas are assessed, can be used to further validate the material-specific brain areas found during LTM retrieval.

If task-irrelevant associations become coactivated during retrieval, then contrasting the congruent (associated with two materials, but response-congruent) with the neutral (associated with only one material type) condition should

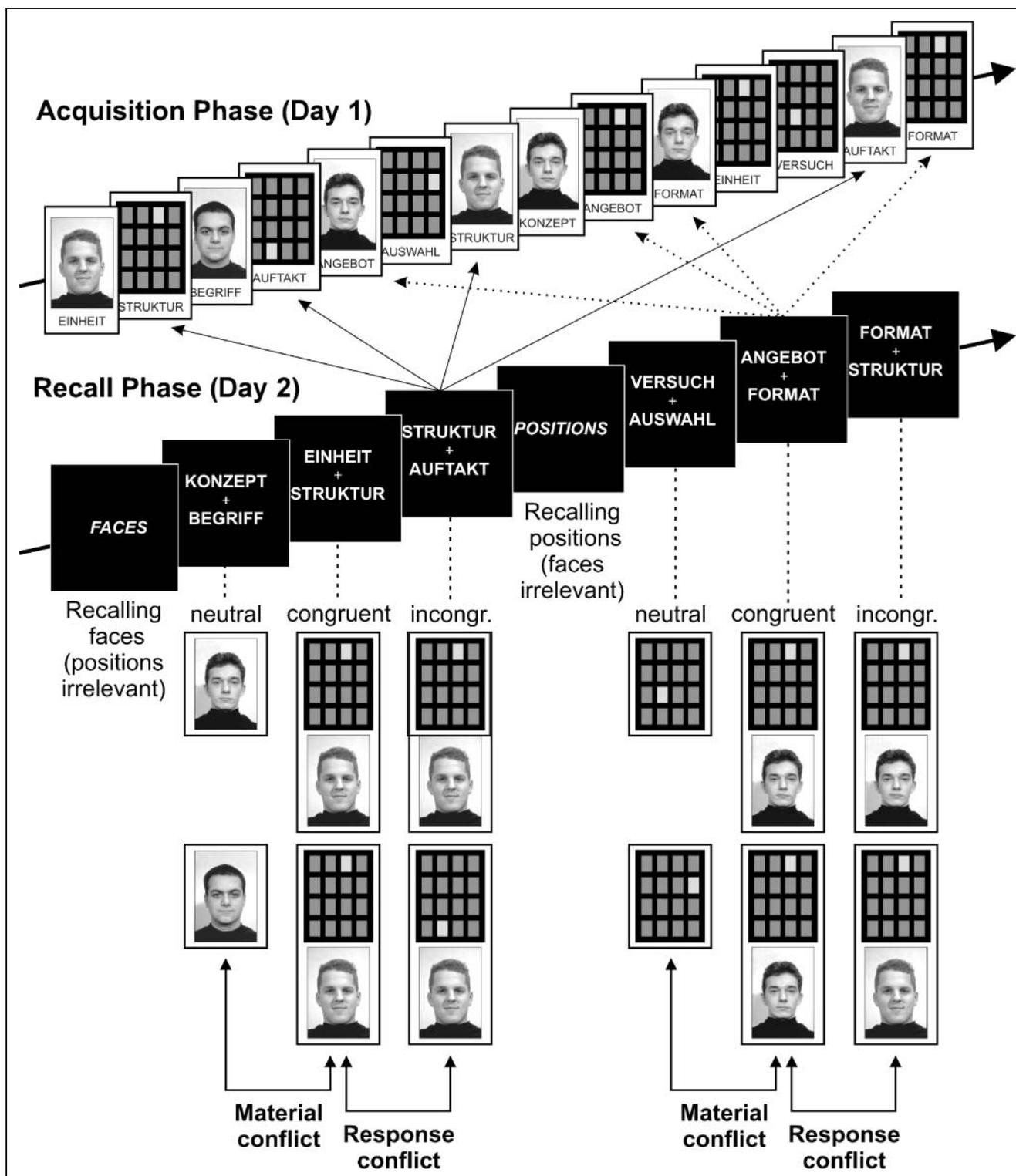


Figure 1. Material and design. Top: Stimulus sequence of the acquisition and recall phases. In the acquisition phase, associations between words and faces and words and spatial positions had to be learned. In the retrieval phase, only words were presented as retrieval cues for recalling faces and positions. A cue presented before miniblocks of six trials indicated which material had to be recalled. Depending on the cue, participants had to indicate by a button press whether two words were associated with the same face or the same position, respectively. Three conditions were realized (see bottom part of figure): In neutral trials, only items of one material type were associated with the words. In both examples shown in the figure (faces on the left and positions on the right), the correct response is “different”. In congruent and incongruent trials, words were associated with items from both material types, leading to retrieval interference. In both examples for the congruent conditions, the correct response is “same.” Note that here the comparison of items from the irrelevant material type would imply the same response. In contrast, in incongruent trials, the comparison of irrelevant items would imply a different response, leading to a response conflict. The numbers of “same” and “different” trials were equal for all three conditions.

lead to activation also in areas representing LTM representations of the irrelevant material type. This should result in retrieval interference (reflected by larger RTs), which, in turn, should activate frontal control areas, such as the medial and lateral PFC (see, e.g., Egner & Hirsch, 2005; Kerns et al., 2004; Botvinick et al., 2001; MacDonald, Cohen, Stenger, & Carter, 2000). Contrasting the incongruent (associated with two materials, but response-incompatible) with the congruent condition should reveal activation in control areas that are specific for processing response conflict. Moreover, we are also interested in how conflicts are resolved. Theoretically, this could be accomplished by boosting the activation of the relevant and/or by suppressing the activation of the irrelevant material type. Again, the topographies and the activation pattern in the target areas for the relevant and irrelevant material types should help to address this issue.

Participants

Twenty-two right-handed students of the University of Marburg, aged between 19 and 28 years, participated in both the fMRI and EEG experiments. All participants were native speakers of German, had normal or corrected-to-normal vision, and gave informed consent. For the EEG analysis, six participants had to be excluded because of too few trials for averaging (i.e., more than 50% of the trials had to be excluded because of artifacts, excessive eye blinks, and erroneous responses), yielding a final EEG sample of 16 participants (5 men and 11 women, mean age = 21.06 years). For the fMRI analysis, two participants had to be excluded because of technical problems. Thus, the final fMRI sample comprised 20 participants (6 men and 14 women; mean age = 20.9 years). Fifteen participants were included in both the EEG and fMRI analyses.

Stimuli, Task, and Procedure

Acquisition Phase

Participants learned associations between 64 words (nouns) and 8 faces and 8 positions. The words were taken from a list of nouns for which normative ratings on vividness, concreteness, and meaningfulness had been obtained from a representative German sample (Hager & Hasselhorn, 1994). Only highly abstract words (e.g., "KONZEPT," concept in English) were chosen to minimize visual associations that could interfere with the acquisition of new associations. The face stimuli were taken from a standardized picture series (courtesy of Sporer, 1999), consisting of whole head photographs of male students (see Figure 1). The spatial positions were defined by light gray squares in a 4×4 matrix of otherwise dark gray squares. Sixteen words became associated with one face each, and another 16 words with one spatial position each. The remaining

32 words became associated with both a face and a position (64 associations). Word–stimulus pairs were randomly constructed for each participant with the restriction that each stimulus occurred equally often.

Participants learned associations between one word and one stimulus. This also held for words that were associated with both material types. The acquisition phase consisted of three runs of an anticipation learning paradigm. In each run, participants were shown all 96 associations in randomized order. Trials started with a white fixation cross (1.5 sec) followed by a white frame (width = 7.4 cm, height = 6.2 cm) that was divided into an upper and a lower section. In the upper section, a word was displayed (height = 0.6 cm) followed by the presentation of the picture stimulus (width = 3 cm, height = 4.5 cm) in the lower section. Throughout the experimental phases and for both the EEG and fMRI experiments, the words were presented in white uppercase letters on a black background. In the first run (initial presentation of word-stimuli pairs), the picture stimuli appeared after 400 msec. In the following runs, this delay was increased to 3 sec, and participants were told to anticipate the associated stimuli during the delay. All stimuli remained on the screen until the participants started the next trial by pressing a button. Intertrial interval (blank screen) was 1 sec. Participants were provided with enough breaks and could choose their own pace to encode the presented associations. Participants needed between 1 hr 20 min and 5 hr (mean = 2 hr 55 min) to complete the acquisition phase.

Training Phase

During a training phase, immediately following the acquisition phase, participants worked on a feedback-controlled learning procedure until they committed less than 12% errors in two complete sets of 96 trials. On each trial, a word was shown on the left side of the screen (height = 0.6 cm). After a delay of 3 sec, which again served to give participants the opportunity to actively anticipate the learned association, the eight positions, or the eight faces, respectively, were presented on the right side of the screen (in two rows of four items, in which the stimuli were ordered randomly in each trial). Participants had to select the correct stimulus by pressing the respective button. Upon incorrect answers, the correct association was presented for relearning. Again, participants could choose their own pace. They needed between 25 min and 3 hr 34 min (mean = 59 min) to reach the learning criterion. Participants had to work through this procedure once more before the EEG and the fMRI recording until they had reached the criterion again (about 30–60 min). Note that the to-be-learned associations were pseudo-randomly assigned to the experimental conditions in the retrieval phase (neutral, congruent, and incongruent), such that remaining differences in associative strength at the end of the training phase cannot be responsible for

the differences between the experimental conditions in the retrieval phase.

Retrieval Phase

The retrieval phase took place within a week after learning (in most cases on the next 2 days) and consisted of an fMRI and an EEG part (on two consecutive days, with the sequence counterbalanced across participants). The learned associations were retrieved with the words as retrieval cues. Two words were presented simultaneously, and participants had to indicate by a button press whether these words were associated with a common stimulus or not. Participants were instructed to respond as fast and as accurate as possible. Faces had to be retrieved in half of the trials, and positions in the other. Material type was fixed for miniblocks of six trials (i.e., alternating runs with $n = 6$). Before every miniblock, a task cue, that is, the German word “GESICHT” (face in English) or “POSITION” (position in English), was presented. Trials were grouped into runs of eight miniblocks (48 trials). The experimental conditions (neutral, congruent, and incongruent) occurred twice in each miniblock in pseudorandomized order, with the restriction that each condition was presented equally often at the beginning (to control for effects of switching). Word pairs were selected, such that each word appeared equally often (and thus, all faces and positions had to be retrieved equally often). Stimulus type, level of conflict (neutral, congruent, and incongruent), and type of response (same and different) were completely crossed. Moreover, incongruent word pairs (that were associated with different responses for different materials) were presented either in the face or the position task.

Retrieval trials of the fMRI experiment started with a fixation cross. After 2 sec, the word pair appeared for 2 sec with one word above and one word below the fixation cross, followed by 6 sec of fixation cross only. Participants thus had 8 sec to respond to the word pair by pressing one of two buttons on an MRI-compatible (fiber-optic) response device. After these 8 sec, a blank screen followed for 2, 4, or 6 sec (intertrial interval). Before each miniblock, the task cue was shown for 2 sec, followed by a blank screen for 2, 4, or 6 sec. Participants completed four runs, yielding 32 trials per experimental condition.

Retrieval trials of the EEG experiment were similar to the fMRI trials with minor changes only: The fixation cross was presented for 1 sec, followed by the words, and participants had 6 sec to respond (with either the left or right “Ctrl” key of a computer keyboard). This time interval proved to be sufficiently long for retrieval (in less than 1% of the trials, the response could not be given within that time). Participants were instructed to suppress eye blinks throughout the trial. Intertrial interval was 3 sec. Before each miniblock, the task cue was shown for 2 sec, followed by a blank interval of 3 sec. Miniblocks were separated by intervals of 4 sec. Runs were doubled (eight runs

with 48 trials each) to have enough trials for the ERP analysis (64 trials for each experimental condition).¹ Participants were given the opportunity to have a short break between the runs. They needed about 1.5 hr to complete the retrieval phase.

Localizer Task

Trials of the fMRI localizer task consisted of a fixation cross shown for a variable duration of 2.5–5 sec (randomly varied in steps of 500 msec), followed by a face or a position for 1.5 sec. Within this interval, participants had to perform a simple visual discrimination task in which they had to indicate by a button press whether the presented stimulus was a face or a position. For this task, eight new faces and eight new positions were used. The functional localizer consisted of 64 trials.

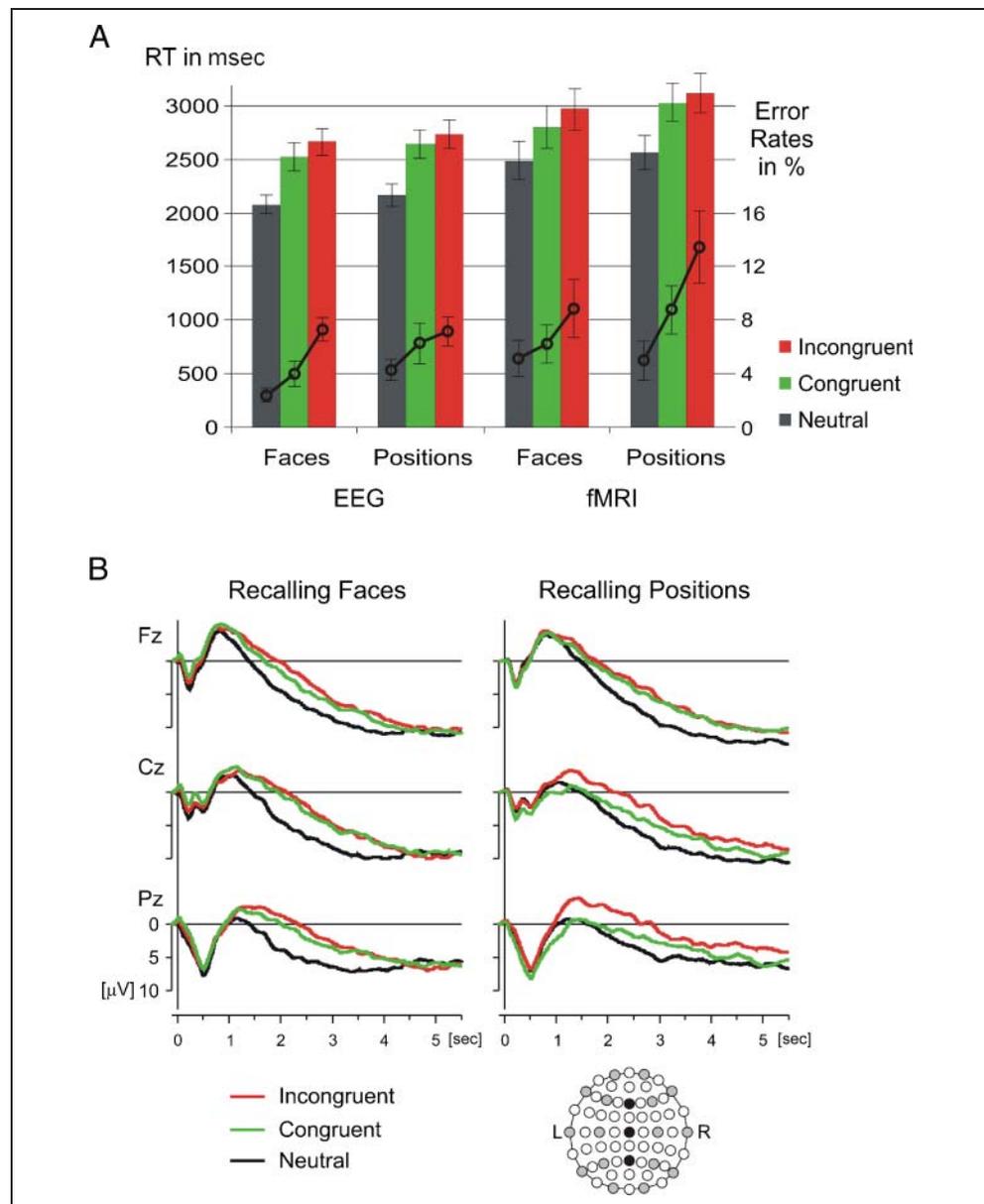
EEG Recording and Analysis

The EEG was recorded from 61 Ag–AgCl electrodes inserted into an elastic cap (EasyCap, Munich, Germany) with predefined electrode positions, extrapolated from the 10–20 system (Jasper, 1958). The electrodes were referenced to the nose tip. The horizontal and vertical EOG was monitored with electrode pairs attached to the outer canthi of both eyes and the suborbital and supraorbital ridges of one eye. The left or right mastoid served as ground. Impedances were kept below 5 k Ω . Recording and digitization (sampling rate = 500 Hz, 40 Hz lowpass filter, 50 Hz notch filter) was done with two 32-channel DC amplifiers (SYNAMPS, NeuroScan, Charlotte, NC) and NeuroScan software Acquire. After every run, a DC reset of the EEG was performed. Drift artifacts were corrected by a regression method (Hennighausen, Heil, & Rösler, 1993). The EEG was segmented into epochs of 5600 msec, starting at 100 msec before the onset of the word. Epochs containing eye blinks (detected by means of cross correlations with a template) or other artifacts (detected by a threshold criterion, that is, a voltage range of >200 μ V within a segment) were removed. ERPs were extracted by averaging epochs separately for participants, electrodes, and experimental conditions and referenced to a 100-msec baseline preceding the onset of the cue. Only trials with correct responses were used. All averages were based on a minimum of 32 trials (mean = 49 trials).

For the statistics, ANOVAs were calculated separately for consecutive time windows of 250 msec length. These time windows started 1000 msec after the onset of the retrieval cue and contained the complete slow wave.² Nineteen standard electrodes according to the 10–20 system were used. These were uniformly distributed over the scalp (see Figure 2) and were sufficient to capture potential topographical differences.

The analyses were run in a hierarchical manner: In the first step, “overall” ANOVAs (see Table 1) were computed

Figure 2. Evidence for material and response conflict from the behavioral data and slow ERPs. (A) Shown are RTs and error rates separately for recalling faces and positions in the EEG and fMRI parts. For both material types and methods, RTs and error rates increased with increasing conflict. Error bars indicate standard errors of the mean. (B) ERPs for three midline electrodes, showing a pronounced parietal positivity around 500 msec followed by a slow potential whose amplitude increased with conflict. The amplitude was more negative during material conflict (when an irrelevant association was additionally associated with the retrieval cue) and further increased during response conflict (when the responses implied by the irrelevant and the relevant associations were different). The material-specific topographies of these increases are delineated in the following figures. Negativity is plotted upwards.



separately for each material type with the repeated measurement factors of Conflict Level (neutral, congruent, and incongruent) and Electrode (19 levels). If this ANOVA signaled a main effect of Conflict Level and an interaction between Conflict Level and Electrode, then subordinate analyses were run. Two contrasts were defined: Comparing the congruent and the neutral conditions testing for material conflict and comparing the incongruent and the congruent conditions testing for the response conflict. “Local” *t* tests, that is, for each electrode, were calculated only for those time windows in which the superordinate ANOVA had signaled significant differences between the conditions. To test for topographical differences between the two material types, analyses comparing faces and positions were run for the respective effects. Furthermore, these analyses were also calculated with *z*-standardized values (see McCarthy & Wood, 1985).

All *F* statistics were corrected according to Huynh and Feldt (1976). The uncorrected degrees of freedom, the corrected *p* value, and the respective ϵ values are reported. We only interpreted effects that were significant (with $p < .05$) in at least two consecutive time windows. “Marginally significant” effects, that is, with $p < .1$, were included only if they were embedded in a longer sequence of significant time windows. For a sequence of significant time windows, only the smallest and the largest *F* values are reported (referred to as min *F* and max *F*).

fMRI Acquisition, Preprocessing, and Statistical Analysis

Anatomical and functional imaging was performed with a 1.5-T MR scanner (Signa, GE Medical Systems, Pittsburgh, PA).

Table 1. Analysis of the Slow Potentials: Summary of the Repeated-Measures ANOVAs

<i>Analysis</i>	<i>Effect</i>	<i>Time Windows (msec)</i>	<i>df</i>	<i>F^a</i>	<i>p</i>	<i>ε</i>
<i>Faces</i>						
Overall	Conflict	1750–3500	2, 30	3.35	.0486	1.0
			2, 30	8.64	.0014	.9356
	Conflict × Electrode	1750–3500	36, 540	1.92	.0840	.1693
			36, 540	2.73	.0066	.2413
Material conflict	Conflict	1750–3500	1, 15	5.28	.0364	
			1, 15	17.60	.0008	
	Conflict × Electrode	1750–3000	18, 270	2.14	.0884	.2170
			18, 270	4.04	.0043	.2122
Response conflict	Conflict	–				
	Conflict × Electrode	–				
<i>Positions</i>						
Overall	Conflict	1250–3250	2, 30	4.59	.0211	.9282
			2, 30	9.39	.0016	.8292
	Conflict × Electrode	1250–3250	36, 540	1.61	.0976	.3117
			36, 540	3.94	.0035	.1352
Material conflict	Conflict	2250–3250	1, 15	4.84	.0439	
			1, 15	6.94	.0188	
Response conflict	Conflict	1250–2500	1, 15	3.39	.0855	
			1, 15	8.14	.0121	
	Conflict × Electrode	1250–2500	18, 270	2.81	.0500	.1674
			18, 270	6.26	.0007	.1897

^aFor each effect, two *F* values, that is, the smallest and the largest *F* values within the significant interval as well as the respective *p* and ϵ values, are reported.

Anatomical whole-head images were acquired from 124 axial slices (1.4-mm thick) using a fast-spin gradient-echo sequence (field of view = 240 × 180 mm, echo time/repetition time = 4.2/11.1, 256 × 192 acquisition matrix, in-plane resolution = 0.9375 × 0.9375 mm). Functional images were acquired with 19 transversal slices covering the whole brain with a T2-weighted EPI sequence (repetition time = 2 sec, echo time = 40 msec, flip angle = 90°, field of view = 240/240 mm, matrix = 64 × 64, slice thickness = 5 mm, interslice gap = 1 mm, in-plane resolution = 3.75 × 3.75 mm) using a standard quadrature head coil. Participants' heads were immobilized by a soft foam pad to minimize head movements and the experimental stimuli were projected on a canvas they could see via two mirrors. Participants lay in the scanner for about 75 min, during which five runs (four retrieval runs followed by the functional localizer task) and the anatomical reference (after the second run) were recorded.

Preprocessing and statistical analysis was performed with BrainVoyager2000/QX (www.brainvoyager.com). The first four volumes of each run were discarded to allow for signal equilibration. After motion and slice scan time correction, temporal filtering (0.01 Hz highpass) and linear trend removal, the functional data were aligned with the anatomical reference from the same session, transformed into Talairach space (Talairach & Tournoux, 1988), spatially smoothed with a Gaussian kernel (FWHM = 8 mm), and subjected to voxelwise general linear models with separate experimental regressors for neutral, congruent, and incongruent face and position trials. To account for the fact that RTs varied substantially across trials, the experimental regressor functions were adjusted to the trial-specific RTs by convolving the model hemodynamic response function (HRF; Boynton model function with delta = 2.5, tau = 1.25) with a boxcar function with length = RT (“RT-convolved HRF analysis”; see, e.g., Christoff et al., 2001).

The responses to the fixation crosses and miniblock cues (2-sec boxcar functions convolved with the model HRF) were modeled as confound predictors. Contrasts between conditions were computed with random effects analyses with a threshold of $p < .001$, uncorrected (if not stated otherwise). Only activation clusters consisting of more than 20 contiguous voxels were considered (as can be seen in Tables 2 and 3, all reported activations are well above this threshold). Statistical maps were projected on a slightly inflated cortex reconstruction of one participant, on which concave curvature (i.e., sulci) appears in dark and convex curvature (i.e., gyri) in light gray.

RESULTS

Evidence for Material and Response Conflict from the Behavioral Data and Slow ERPs

RTs and error rates are presented in Figure 2A. For the RT analysis, only trials with correct responses were used. As can be seen, the level of conflict had a substantial effect on both error rates and RTs: Both measures increased when two materials are associated with the words (congruent vs. neutral; material conflict) and further increased when they lead to different responses (incongruent vs. congruent; response conflict). The data were submitted to ANOVAs with factors material type (recalling faces vs. recalling positions) and level of conflict (neutral, congru-

ent, and incongruent). ANOVAs for RTs revealed significant main effects of conflict level in the EEG, $F(2, 30) = 113.09$, $p < .0001$, $\epsilon(H-F) = .7879$, and the fMRI, $F(2, 38) = 35.38$, $p < .0001$, $\epsilon(H-F) = .6896$. The interactions with material type were not significant. Planned t tests revealed that the effects congruent versus neutral and incongruent versus congruent were highly significant (all $ps < .01$). Moreover, the ANOVAs also revealed main effects for material type with $F(1, 15) = 7.97$, $p = .0129$ and $F(1, 19) = 7.17$, $p = .0149$, for the EEG and the fMRI part, respectively. These indicate that RTs were slightly larger for recalling positions than for recalling faces.

Error rates were generally low, but showed basically the same effects as the RTs: ANOVAs revealed significant main effects of conflict level in the EEG, $F(2, 30) = 13.89$, $p < .0001$, $\epsilon(H-F) = .9700$, and the fMRI data, $F(2, 38) = 10.50$, $p = .0002$, $\epsilon(H-F) = .9168$. Neither the main effects material type nor the interactions were significant. Planned t tests again revealed that the contrasts of material conflict and response conflict were both significant ($ps < .05$) in both parts.

We also directly compared the behavioral data of the EEG and the fMRI sessions. Note that the stimulus timing and numbers of trials differed between the EEG and fMRI retrieval sessions, which could affect the retrieval processes. However, an analysis of the material and response conflicts (with the 15 participants that were included in both analyses) did not reveal any significant differences

Table 2. Location (Brodmann's Area and Talairach Coordinates), Mean t Value, and Number of Significantly Activated Voxels of Brain Areas in the Contrasts that Were Used to Delineate Neural Correlates of Recalling Faces and Spatial Positions ($p < .001$)

Region	BA	x	y	z	t	Voxels
<i>Neutral ("No-Conflict") Conditions</i>						
Faces > Positions						
L/R posterior cingulate gyrus	30	-7	-55	26	3.85	6,847
L superior temporal gyrus	22	-44	-53	20	3.74	3,096
Positions > Faces						
L superior parietal lobe	7	-18	-72	46	3.50	283
R superior parietal lobe	7	14	-72	43	3.46	393
<i>Functional Localizer</i>						
Faces > Positions						
L/R posterior cingulate gyrus	30/31/17	-4	-71	9	6.14	23,551
L fusiform gyrus	19/37	-38	-55	-13	4.41	4,409
R fusiform gyrus	19/37	32	-49	-11	5.07	2,964
Positions > Faces						
L superior parietal lobe	7	-21	-69	51	4.41	3,078
R superior parietal lobe	7	18	-68	42	5.22	11,273

L = left, R = right, BA = Brodmann's area.

Table 3. Location (Brodmann's Area and Talairach Coordinates), Mean *t* Value, and Number of Significantly Activated Voxels of Brain Areas in the Contrasts that Were Used to Detect Neural Correlates of Conflicts Resulting from Coactivation of Irrelevant Stimulus Representations (Material Conflict: Congruent > Neutral) and from Incompatibility of the Responses to the Relevant and Irrelevant Stimulus Representations (Response Conflict: Incongruent > Congruent)

Region	BA	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>	Voxels
<i>Congruent > Neutral (p < .001)</i>						
Faces						
L posterior cingulate gyrus	30	-16	-57	16	3.63	561
L superior parietal lobe	7	-33	-69	37	3.59	1491
L middle/inferior frontal gyrus	8/9	-45	16	35	4.30	1750
L medial frontal gyrus	6	-5	11	53	4.61	852
Positions						
L posterior cingulate gyrus	30/23	-11	-50	16	3.90	6851
R posterior cingulate gyrus	30/23	13	-56	20	3.67	1308
L superior parietal lobe	7	-32	-57	33	4.21	4198
L middle frontal gyrus	8/9	-40	6	37	4.08	5098
L middle frontal gyrus	46	-43	28	28	3.59	765
L superior frontal gyrus	6	-31	1	56	3.79	2521
L medial frontal gyrus	6	-6	13	53	3.86	2773
L insular cortex	-	-30	25	11	3.82	986
R insular cortex	-	31	23	10	3.68	835
<i>Incongruent > Congruent (p < .01)</i>						
Positions						
R superior parietal lobe	7	24	-60	32	2.68	519
L middle frontal gyrus	8	-45	13	46	2.59	360
L medial frontal gyrus	8	-5	38	50	2.88	4590
Faces						
(No significant activations)	-	-	-	-	-	-

L = left, R = right, BA = Brodmann's area.

between the sessions. All in all, the behavioral data proved the successful induction of material and response conflicts for both materials and methods.

Figure 2B shows the ERPs for the three conditions, separately for recalling faces and positions: As can be seen, the most pronounced differences between the three conditions emerged between 1000 and 4500 msec as modulations of slow potential amplitude (following a positive ERP deflection around 500 msec with a parietal maximum). The focus here will be on the amplitude differences of this slow wave.

Consistent with the behavioral data, the slow potential amplitude increased with increasing conflict, indicating increasing overall cortical activation. The mere existence of an irrelevant association elicited increased slow wave

amplitudes compared with the neutral condition. Furthermore, when the irrelevant association implied a response that was different from the response to the relevant association, there was an additional amplitude increase. Moreover, visual inspection suggests that these increases have different time courses for the two material types. Therefore, ANOVAs, which are aimed at delineating in which time windows effects are significant, were run separately for the two material types. In the first step, overall ANOVAs with three levels of conflict (neutral, congruent, and incongruent) were calculated for each material type. Significant differences between the conflict levels were found between 1750 and 3500 msec for faces and between 1250 and 3250 msec for positions (see Table 1). As will be shown in the following paragraphs, these amplitude modulations

reflect more than just general effects of task difficulty, because the topographies of the effects differed for the material and conflict types.

Material-specific Neural Correlates of Retrieving Faces and Spatial Positions

To delineate indicators of material-specific retrieval processes, we compared the “no-conflict” (neutral) conditions, in which either faces or spatial positions had to be retrieved without interference from the other material. ANOVAs with factors material type and electrode revealed significant interactions between 1750 and 3750 msec, min

$F(18, 270) = 2.95, p = .0232, \epsilon = .2415$; max $F(18, 270) = 5.01, p = .0004, \epsilon = .2930$.

As indicated by the topographic maps in Figure 3A (left), the distribution of the negative maxima of slow ERPs (blue shading) differed between the material types: Recalling faces elicited two maxima, one over the left frontal and the other one over the occipital-to-parietal cortex. In contrast, recalling positions elicited only one broad maximum over the occipital-to-parietal cortex. To corroborate this topographical difference, we computed an ANOVA with z -standardized amplitudes. This analysis again revealed an interaction between material type and electrode, $F(18, 270) = 2.88, p = .0349, \epsilon = .2023$. A predominately

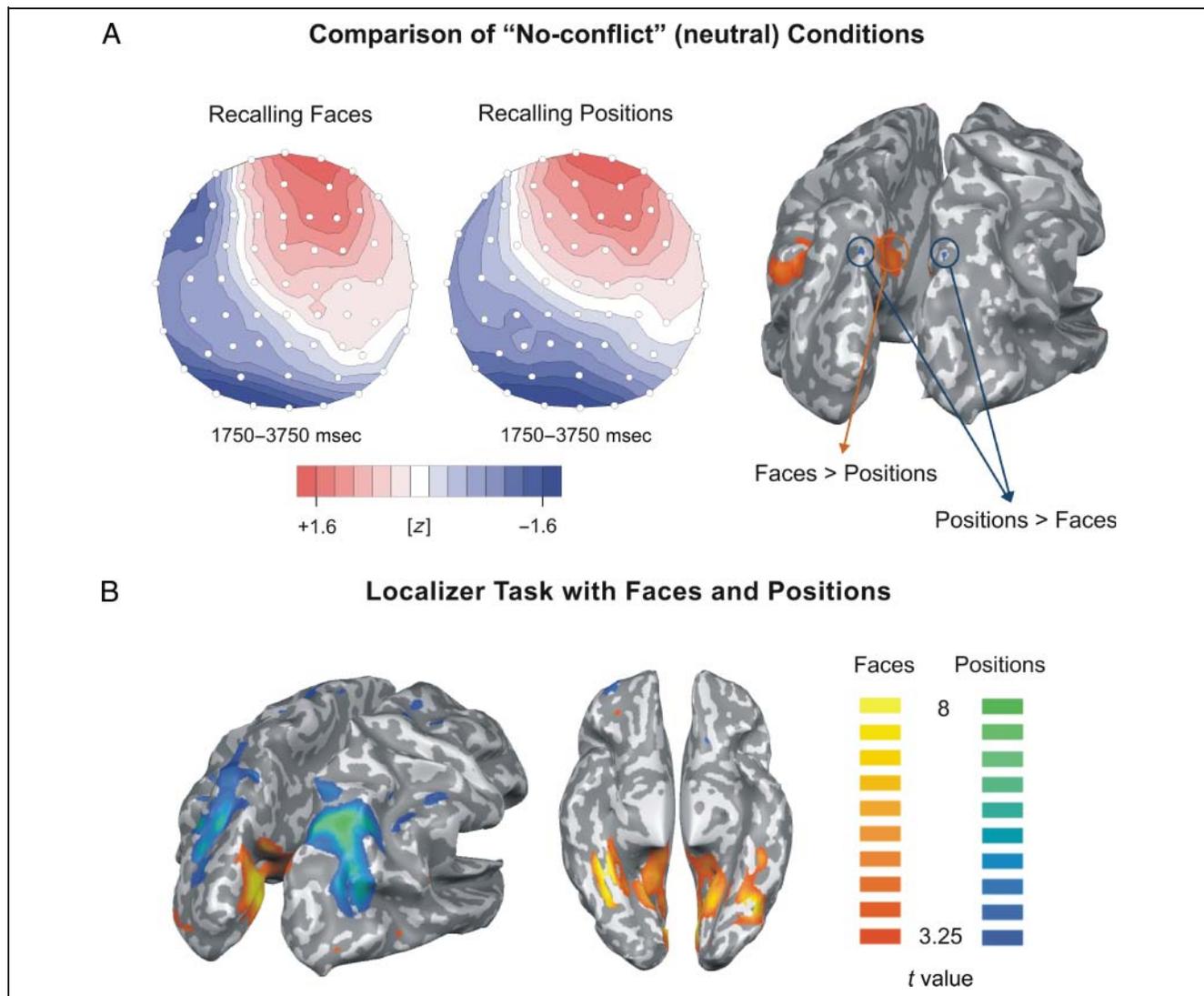


Figure 3. Overview of material-specific brain areas and ERP topographies for faces and spatial positions. (A) Comparison of the “no-conflict” (neutral) conditions for recalling either faces or spatial positions, revealing topographical dissociations in the EEG as well as in the fMRI. In the EEG, recalling faces elicited two maxima, one over the left frontal cortex and the other one over the occipital-to-parietal cortex (blue shadings). In contrast, recalling positions elicited only one broad maximum over the occipital-to-parietal cortex. The ERP maps were computed from all 61 scalp electrodes. In the fMRI, stronger brain activations were found in the posterior cingulate cortex and the left superior temporal gyrus (BA 22) for recalling faces (orange) and in the left and right superior parietal lobes (BA 7) for recalling positions (blue). For color scale and t values, see below. (B) Contrasting the retrieval of faces and positions in the fMRI localizer task revealed stronger activation for positions in the superior parietal lobes (BA 7) and for faces in the posterior cingulate cortex and the fusiform gyrus.

left frontal maximum for faces and an occipital-to-parietal maximum for positions are fully consistent with results from a previous EEG study employing the same face and position stimuli (Khader, Heil, et al., 2005). On the basis of the topographical difference found for the neutral conditions, we will interpret a predominately left frontal EEG topography as an indicator for retrieving faces and an occipital-to-parietal topography as an indicator for retrieving positions.

In the fMRI, we computed a contrast between the neutral conditions for faces versus spatial positions (shown in Figure 3A, right). For faces, stronger brain activations were found in the posterior cingulate cortex and the left superior temporal gyrus, whereas for recalling positions stronger activations were found in the left and right superior parietal lobes (BA 7; see Table 2). In addition to the comparison of the neutral conditions, we also employed the functional localizer task. Contrasting the neural response to faces versus spatial positions (see Figure 3B and Table 2) revealed activations in areas that were already found in the contrast of the neutral conditions (see Figure 3A), that is, the left and right superior parietal lobes for positions and the posterior cingulate cortex for faces, albeit all of these activations were generally much more widespread. For faces, an additional activation was found in the left and right fusiform gyri. All in all, both the comparison of the neutral conditions and the comparison of the localizer scans revealed common material-specific brain areas, although, because of the obvious differences in the underlying cognitive processes, the two comparisons did not result in exactly the same activation patterns. Considering the commonalities between the localizer and the comparison of the neutral conditions, we assume the posterior cingulate cortex to be indicative for the retrieval of faces and the superior parietal lobes to be indicative for the retrieval of spatial positions. These activations are fully consistent with a previous fMRI study employing the same material (Khader, Burke, et al., 2005).

Neural Correlates of Material Conflict

In congruent trials, the retrieval cues are associated with both material types, whereas in neutral trials, they are associated with one material type only. A contrast of congruent and neutral trials should therefore be suited to detect a possible coactivation of irrelevant information in the congruent condition that, in turn, could underlie the increased RTs and error rates found in this condition.

In the ERPs, congruent trials elicited a larger negative slow wave than neutral trials. For retrieving faces, ANOVAs contrasting these two conditions within the significant interval of the superordinate ANOVA, that is, between 1750 and 3500 msec, revealed a significant main effect of conflict for the whole interval and a significant interaction with electrode from 1750 to 3000 msec (see Table 1). "Local" *t* tests, that is, calculated for each electrode and time window, revealed significant effects at almost all electrodes

between 1750 and 3000 msec (except for the right frontal electrodes Fp2 and F8), but with a pronounced maximum at posterior electrodes. This is also illustrated in the topographic map in Figure 4A: When recalling faces interference by positions produced the maximum EEG response over the posterior cortex.

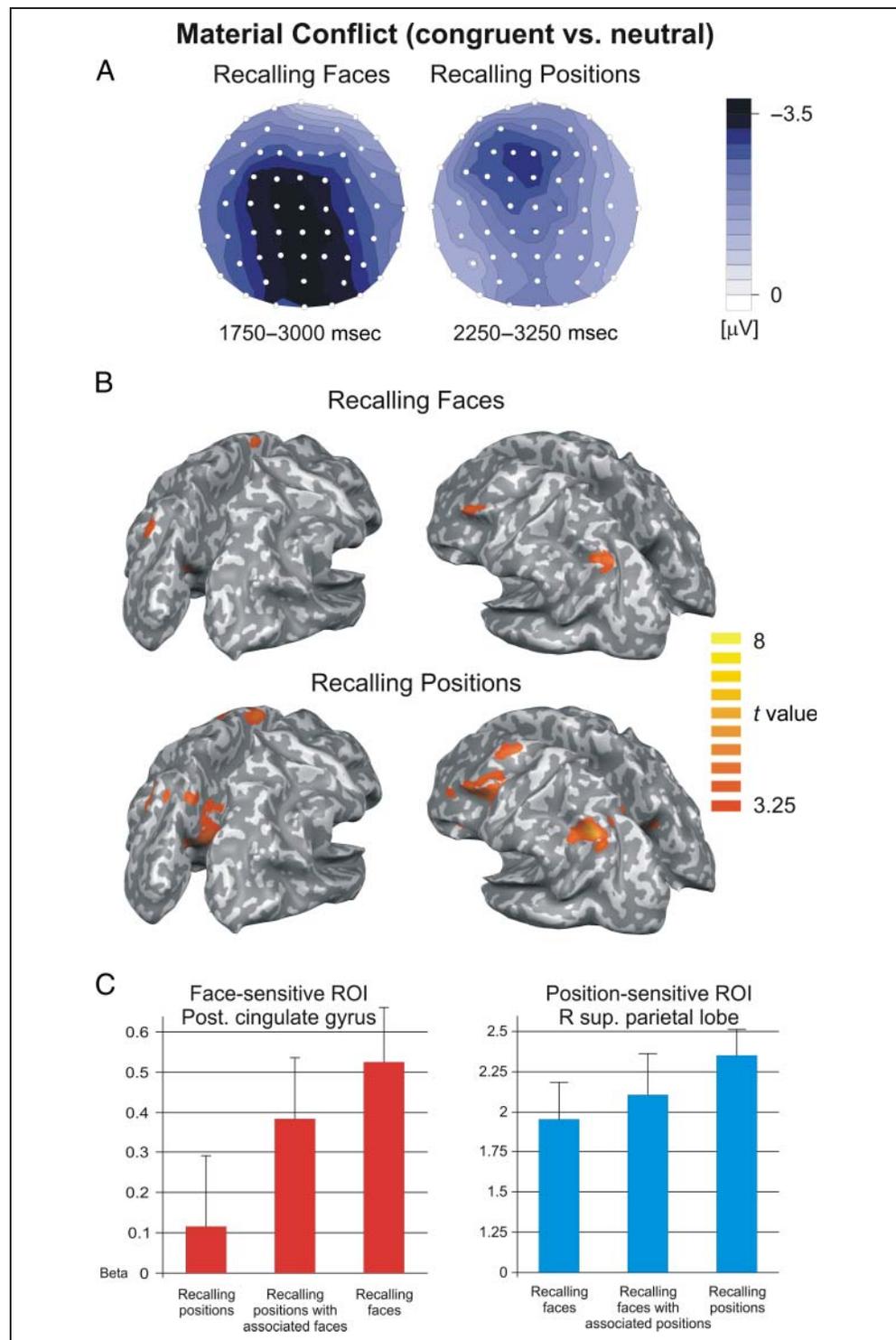
For positions, the difference between congruent and neutral trials was significant between 2250 and 3250 msec (see Table 1). Local *t* tests revealed that the effect is also widely distributed with significant differences at frontal, central, and parietal electrodes. However, in contrast to the effect for faces, which was largest at central and parietal electrodes, the effect for positions had a clear frontal maximum and decreased over central to parietal electrodes. To directly test for these different topographical gradients, we ran an ANOVA with three electrode clusters, that is, frontal, central, and parietal, that each included a row of seven medial electrodes (inferior ones excluded). This ANOVA did not reveal any main effect, but a marginally significant interaction between material type and electrode row, $F(2, 30) = 3.54, p = .0743, \epsilon = .5546$, that supports the different gradients. This also held for the analysis with *z*-standardized values, $F(2, 30) = 3.41, p = .0742, \epsilon = .6141$.

To summarize, as can be seen in Figure 4A, the material contrast yielded different topographies of slow ERPs for the two material types: For recalling faces, a broad posterior maximum emerged, whereas for recalling positions a (left) frontal maximum was found. As outlined above, an occipital-to-parietal topography is typical for the activation of the representations of spatial positions, whereas a predominately left frontal topography is typical for the activation of face representations. Accordingly, the material-specific topographies of the material conflicts are consistent with an activation of representations of the irrelevant material type and therefore suggest that irrelevant associations become coactivated during material conflict.

The notion of a coactivation of irrelevant associations during material conflict is further substantiated by the corresponding fMRI results. As shown in Figure 4B (see also Table 3), recalling faces in the congruent compared with the neutral condition activated the left superior parietal lobe, a brain region that was found to be more active for positions than for faces in both the comparison of the neutral conditions and in the localizer (see above). We therefore take this as evidence for the activation of the irrelevant material, that is, positions. In contrast, recalling positions during material conflict activated the posterior cingulate cortex. Again, this neural response suggests an activation of the irrelevant material, because this brain area has been found to be more strongly activated by faces.

As can be seen in Figure 4B, left superior parietal lobe activation was also found for recalling positions and posterior cingulate activation for recalling faces, indicating a stronger activation of the relevant material in congruent compared with neutral trials. These activations, however,

Figure 4. Neural correlates of material conflict. (A) Different ERP topographies for recalling faces and positions. When faces were relevant, the difference between congruent and neutral had a broad posterior maximum, whereas when positions were relevant, this contrast was maximal at (left) frontal electrodes. These material-specific topographies are consistent with an activation of representations of the irrelevant material type. (B) Stronger fMRI activation for the congruent compared with the neutral condition: Recalling faces activated the left superior parietal lobe, which can be regarded as a marker for the activation of irrelevant positions. In contrast, recalling positions activated the posterior cingulate cortex, which can be regarded as a marker for the activation of irrelevant face representations. As can be seen, left superior parietal activation was also found for recalling positions and posterior cingulate activation for recalling faces, suggesting that the relevant material becomes increasingly activated when compared with the neutral condition. In addition to the posterior activations there was also an increased activation in frontal control areas, that is, the left medial frontal gyrus and the left middle and inferior frontal gyri, for both material types. (C) ROI analysis. Mean beta values extracted from material-specific brain regions that were defined by contrasting the respective “neutral” (no-conflict) conditions. The bar graphs show that the face-specific region was least active when only positions were associated with a retrieval cue. However, when positions were relevant, but faces were additionally associated with the retrieval cue, then the activation increased. The largest activation was elicited when faces were task-relevant. Corresponding effects were found in the position ROI, respectively (right side).



were less widespread (reflected by the numbers of significant voxels) than the corresponding activations for the irrelevant material, that is, 561 voxels in the left posterior cingulate cortex versus 1491 voxels in the left superior parietal lobe during material conflict for faces, but 6851 voxels in the left posterior cingulate cortex versus 4198 voxels in the left superior parietal lobe during material conflict for positions. The smaller activation of the relevant compared with the irrelevant material in congruent compared with neutral trials is consistent with the EEG results, where the topography was dominated by the irrelevant material.

In addition to the whole-brain analysis, an ROI analysis also substantiated the claim that task-irrelevant material becomes coactivated during material conflict. As we regard the contrast between the neutral conditions to be indicative of a material-specific activation of LTM representations during recall, we defined the most active regions of this contrast as ROIs, that is, the posterior cingulate gyrus for the retrieval of faces and the right superior parietal lobe for the retrieval of spatial positions (cf. Figure 3A, right side). Subsequently, we extracted the beta values from these regions during the “pure” (conflict-free) retrieval trials, as well as during conflict trials (i.e., when two materials are associated, but only one is task relevant). As can be seen in Figure 4C (red bars, left side), the face-specific region was least active when only positions were associated with a retrieval cue (position/neutral). However, when positions were relevant, but faces were additionally associated with the retrieval cue (position/congruent and position/incongruent), activation increased, reflecting coactivation. The largest activation was elicited, as expected, when faces were task-relevant (all face-retrieval trials). Both effects were significant with $p < .01$. Fully consistent with these results from the face ROI, we found corresponding increases in the position ROI ($p = .08$ and $p < .01$, respectively; see blue bars on the right side of Figure 4C).

So far, the analysis of the material conflict revealed that LTM representations that are associated with a specific retrieval cue become activated even when they are task irrelevant. This, in turn, should lead to a recruitment of prefrontal control processes that serve to disentangle the relevant and irrelevant associations. The fMRI analysis supports this assumption: the left posterior medial frontal gyrus (BA 6, pre-SMA) and the left middle and inferior frontal gyri (BA 8 and BA 9; dorsolateral PFC [DLPFC]) became activated under material conflict. Interestingly, these activations were material unspecific, that is, they were found in both the face and the position contrasts with similar locations (see Figure 4B, as well as the Talairach coordinates in Table 3; see also Figure 6). As outlined above, parts of the medial and lateral PFC are regarded as essential for monitoring and controlling conflict. Our data suggest that this system becomes recruited irrespective of the conflicting information being internal (memory representations) or external (perceived stimuli).

Previous studies inducing conflict on the basis of LTM representations have found the VLPFC to be involved in

controlling interference (e.g., Souza et al., 2009; Kuhl et al., 2008; Wimber et al., 2008; Nee et al., 2007; see Badre & Wagner, 2007, for a review). However, we did not find any conflict-related signal modulations in the VLPFC, even when the significance level was lowered to $p < .05$. We also conducted an ROI analysis on the VLPFC by extracting BOLD responses from an anatomical BA 45 ROI. These signals, however, also provided no evidence for a systematic conflict-related activation.

The claim that the found frontal activations are closely related to LTM-based conflict could be further validated by demonstrating that they are systematically related to the behavioral effect of material conflict. For this analysis, we extracted the mean beta values from the activated medial and lateral prefrontal regions for each participant and calculated the conflict-related signal increase by computing difference scores congruent minus neutral. The resulting difference scores showed significant positive correlations with an individual’s behavioral material conflict (all $p < .05$). For retrieving positions, the correlations amounted to $r = .50$ for the medial PFC and to $r = .55$ for the lateral PFC. Similar correlations were observed for retrieving faces, with $r = .44$ and $r = .49$ for the medial and lateral PFC, respectively. These correlations show that individual differences in the behavioral material effect go along with the degree of activation increase in the frontal control areas.

Neural Correlates of Response Conflict

Response conflict can be assessed by contrasting the incongruent with the congruent condition. For both material types, the amplitude of slow ERPs was more negative for incongruent compared with congruent trials. When faces were to be retrieved, this difference was rather small and neither the main effect nor the interaction with electrode reached significance (despite significant behavioral effects). When retrieving positions, the response conflict (both main effect and the interaction with electrode) was significant between 1250 and 2500 msec (see Table 1) and had a clear posterior maximum (see Figure 5A). Local t tests revealed significant differences at parietal and occipital (P3, Pz, P4, O1, and O2), as well as at temporal electrodes (T5 and T6).

In the fMRI, activations for this contrast were generally rather weak and for the $p < .001$ criterion no significant activations were found in posterior representation areas. To find out whether we would find activations that correspond to the posterior EEG topography for positions, we lowered the significance level to $p < .01$. With this criterion, for recalling positions a significant activation was found in the right superior parietal lobe (Figure 5B and Table 3). For faces, no activations were found even with this lowered significance level.

The focus of the parietal activation for positions largely corresponds to the activation found for positions in the contrast of the neutral conditions (cf. the respective

Talairach coordinates in Tables 3 and 2, that is, 24/−60/32 and 18/−68/42). Both this fMRI activation and the corresponding EEG topography, are typical for positions, suggesting that the representations of the relevant material become increasingly activated during response conflict. If this interpretation is valid, then recalling faces under response conflict should show a (left) frontal topography in the EEG. Although the response conflict for faces did not reach significance, a descriptive look at the topography suggests that this effect has a maximum at frontal electrodes (and a second focus over the parietal cortex; see ERPs in Figure 2B) and therefore differs from the posterior maximum when recalling positions.

The response conflict for positions also activated frontal areas: the medial frontal cortex (BA 8; an area superior to the anterior “rostral cingulate zone” as defined by Picard & Strick, 2001) was significant with the conventional criterion of $p < .001$. Furthermore, a small activa-

tion appeared in the lateral PFC, that is, in the left middle frontal gyrus (BA 8/BA 9), when the significance level was lowered to $p < .01$ (see Figure 5B, bottom and Table 3). Thus, the medial and lateral PFC seem to be involved in processing response conflict.

Theoretically, conflict control could be achieved by two mechanisms that bias target representations, that is, by boosting relevant and/or by inhibiting irrelevant representations. The stronger activation of the relevant material shown above supports the first option. In addition, we computed the reversed contrast (i.e., reduced activation for incongruent compared with congruent trials) in the target areas of the irrelevant material, which could have been a sign of the inhibition of irrelevant representations during response conflict. Here, however, no consistent activation was found.

Dissociating Material and Response Conflict in the Prefrontal Cortex

Both the material and the response conflict activated the medial and lateral PFC. However, a superposition map (as shown in Figure 6A) revealed different activation foci in the medial frontal cortex: the activation for the response conflict was located more anterior than the activation for the material conflict. To further substantiate this dissociation, we extracted the beta values for the respective contrasts and ROIs. Figure 6A (left bar chart) shows a dissociation of the material and response conflict (both for recalling positions) in the anterior medial PFC where the response conflict was largest and the posterior medial PFC where the material conflict was largest. This dissociation was substantiated by a significant Type of Conflict \times ROI interaction, $F(1, 19) = 7.731$; $p = .012$. The same held when the response conflict in the anterior medial PFC for recalling positions was compared with the material conflict in the posterior medial PFC for recalling faces (right bar chart), $F(1, 19) = 12.705$; $p = .002$. Thus, different parts of the medial prefrontal cortex are involved in processing interference arising from a coactivation of irrelevant stimulus representations (material conflict) and from incongruity of the responses to the relevant and irrelevant stimulus representation (response conflict). In contrast, the two types of conflict showed overlapping activations in the DLPFC (see Figure 6B).

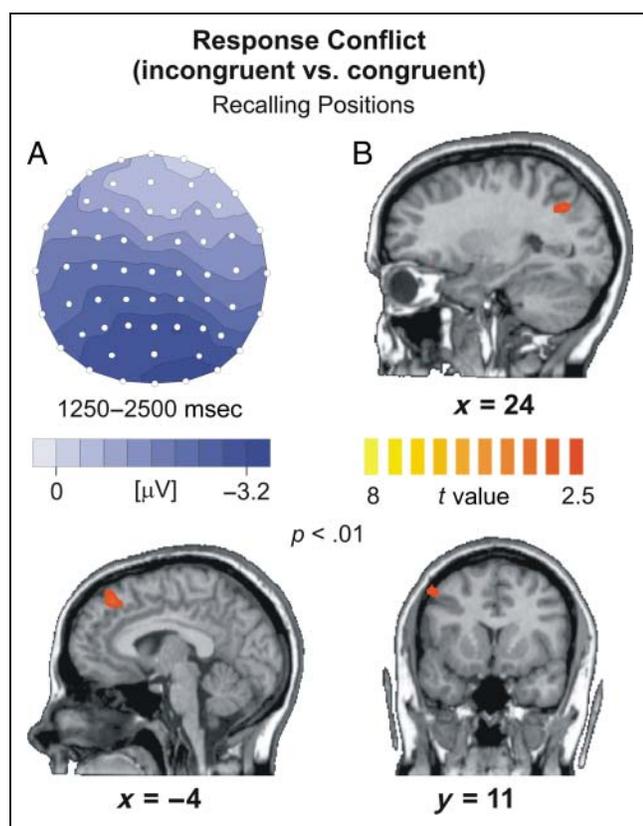
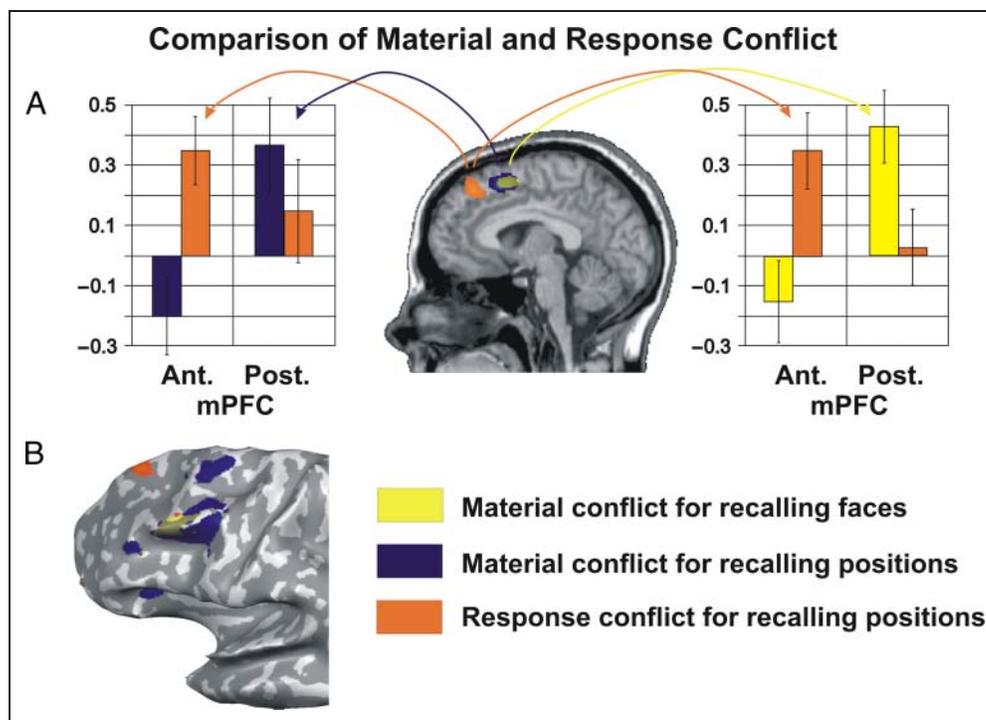


Figure 5. Neural correlates of response conflict. EEG and fMRI evidence for an increased activation of relevant representations and an involvement of frontal control areas during response conflict. (A) For positions, incongruent trials elicited a more negative slow potential with a posterior maximum compared with congruent trials. (B) In the fMRI, this contrast yielded significant activation in the right superior parietal lobe. Both the fMRI activation and the ERP topography are typical for recalling positions, suggesting that the representations of the relevant material become increasingly activated during response conflict. In addition to the activation in the posterior cortex, there was also activation of frontal control areas, that is, the medial and left middle frontal gyri. For recalling faces, no significant EEG and fMRI activations were found in this contrast.

DISCUSSION

How does the cognitive system deal with interference arising in LTM and is this conflict controlled like other forms of conflict? In this study, words became associated either with a face, a spatial position, or both. The resulting experimentally implemented and well-consolidated associative network allowed to fully control the activation of relevant and irrelevant associations during retrieval when only one material type is relevant. The present paradigm

Figure 6. Dissociating material and response conflict in the PFC. Shown are the response conflict contrast for positions and the material conflict contrasts for faces and positions. (A) The activation patterns revealed that response conflict and material conflict activated different regions in the medial frontal cortex (shown is a sagittal slice at $x = -4$). The left bar chart shows the difference of beta values “congruent – neutral” (material conflict) and “incongruent – congruent” (response conflict) in the anterior medial PFC where the response conflict was largest, as well as in the posterior medial PFC where the material conflict was largest (both for recalling positions). This dissociation was substantiated by a significant Type of Conflict \times ROI interaction (see main text). The same holds when the response conflict in the anterior medial PFC for recalling positions is compared with the material conflict in the posterior medial PFC for recalling faces (right bar chart). (B) In contrast to the medial PFC, the two types of conflict showed overlapping activations in the DLPFC.



also allows contrasting memory-based conflict with another type of conflict, that is, conflict arising when the two materials imply different responses. In contrast to the memory conflict, which arises at the level of LTM representations, this conflict arises at the level of response selection.

Our data suggest a coactivation of irrelevant material that leads to retrieval interference: Recalling faces when positions are irrelevant elicited, compared with a neutral condition, an activation pattern that is typical for positions, that is, a parietal topography of slow ERPs and an fMRI activation of the left superior parietal lobe. The same holds when positions are to be recalled and faces are additionally associated. In this case, we found activations that are typical for the activation of face representations, that is, a (left) frontal slow-wave topography and an fMRI activation of the posterior cingulate cortex. The fact that coactivations were found for two different materials and with two different methods shows that it is a general and robust feature of memory retrieval that is not restricted to a specific (or dominant) material type. In the EEG, material specificity could be detected, because we here analyzed slow potentials, which are brain signals that occur for all materials and tasks, but with specific topographies (in contrast to components that are restricted to certain material types, such as the N170 for faces; see Bentin, Allison, Puce, Perez, & McCarthy, 1996). Moreover, the fact that we found converging results with fMRI from the same participants constitutes a cross validation of the found effects.

Our coactivation findings are also consistent with other recent work that found a coactivation of irrelevant material using proactive-interference paradigms (Kuhl, Rissman, Chun, & Wagner, 2011; Öztekin & Badre, 2011). These results complement our findings by showing that coactivation occurs not only in dynamic interference situations in which information is only currently task irrelevant but could become relevant in subsequent trials (as it is the case with our paradigm), but also in more continuous interference situations in which a subset of associations are marked as irrelevant for the whole experiment by instruction.

The coactivation of competing memory representations is accompanied by activations in the left medial frontal gyrus (pre-SMA) and the left middle and inferior frontal gyri. Both areas have been described as areas of executive control that modulate the accessibility of information in the service of current goals and task demands (Koechlin et al., 2003; Botvinick et al., 2001; Miller & Cohen, 2001). Specifically, the “conflict-monitoring model” (Botvinick et al., 2001; MacDonald et al., 2000) proposes that a conflict-monitoring module located in the medial PFC (in the model, ACC) detects any type of processing conflict and subsequently forwards a conflict signal to a control module that, in turn, resolves the conflict. There is much evidence that the lateral PFC is involved in resolving conflict by triggering top-down biasing processes (e.g., Egner & Hirsch, 2005; Kerns et al., 2004; MacDonald et al., 2000). The activation in the medial and lateral PFC in this study, as well as in

other studies on LTM interference (e.g., Kuhl et al., 2008, 2011), suggest that LTM-based interference is processed much like other forms of interference, such as in Stroop and flanker tasks.

Previous studies inducing conflict on the basis of LTM representations have found the VLPFC to be involved in controlling interference (e.g., Souza et al., 2009; Kuhl et al., 2008; Wimber et al., 2008; Nee et al., 2007; see Badre & Wagner, 2007, for a review). One reason for why we found DLPFC activation might be that our task involved accessing pictorial information, whereas many of the studies finding VLPFC activation used conceptual knowledge and verbal material. This would suggest that different domains of representation (pictorial vs. verbal) draw on control processes in different subsections of PFC. Alternatively, whether conflict is induced within or between a domain or stimulus dimension could be responsible for the dissociation in the lateral PFC: Most of the LTM interference paradigms induced conflict within a stimulus domain (e.g., conflict between word pair associations in proactive interference or retrieval practice paradigms) and found activation in the VLPFC, whereas the “on-line” conflict paradigms often induce conflict between stimulus dimensions (e.g., between color and word information in the Stroop task and location and color in the Simon task). Note that our results cannot dissociate between these two explanations (verbal vs. visual information or within vs. between domains), because we used pictorial material and induced conflict between domains. Similarly, in a recent study by Kuhl et al. (2011), LTM interference between two different classes of pictorial information, that is, between faces and scenes, elicited activation in the DLPFC. Further research should address this issue in more detail.

In addition to the activation of the irrelevant material that causes interference and leads to activation in frontal control areas, our data also show that under material conflict the representations of the relevant material become more activated than in the neutral condition. This additional activation suggests that interference is controlled by boosting the task-relevant LTM representations to enhance the contrast between relevant and irrelevant information. Note that there is no need to bias visual processes, because not the stimulus is bivalent, but the association structure in memory. Therefore, the focus of control is at the level of LTM representations.

Let us now turn to the response conflict, that is, interference arising from the fact that different representations imply different responses. As expected, response conflict also activated the medial and left middle frontal gyri, which are assumed to be involved in monitoring and regulating conflict. Furthermore, there was a stronger parietal topography in the EEG and slightly stronger fMRI activation in the right superior parietal lobe for response-incongruent compared with response-congruent trials when positions had to be retrieved. As shown in the Results, these activation patterns are typical for positions and therefore

suggest that under response incongruity the activation of relevant representations become increased, possibly to elevate the “signal-to-noise ratio” of competing decisions.

Besides enhancing activation, inhibition has been proposed to be another mechanism of control, especially of response control (e.g., Aron, 2007), but also for suppressing neural activity of task-irrelevant information during attention (Gazzaley et al., 2005) and memory tasks (Anderson et al., 2004). In this study, however, we did not find evidence for an inhibition of irrelevant representations (i.e., no reduced activation for incongruent compared with congruent trials). This could suggest that the controlled retrieval of competing LTM contents can be accomplished without the inhibition of task-irrelevant representations. However, further research is needed before any final conclusion can be drawn regarding the involved conflict resolution mechanisms.

Overall, for both types of conflict, we found activation in the medial and lateral PFC. However, whereas the activations of the two conflicts overlapped in the lateral PFC, the medial frontal activations were distinct (see Figure 6): Material conflict activated the pre-SMA, whereas response conflict was found to be more anterior, that is, in an area superior to the anterior rostral cingulate zone. This pattern resembles the anterior–posterior gradient observed in other studies. For example, Desmet, Fias, Hartstra, and Brass (2011) report dissociable medial prefrontal areas for conflicts arising on the task versus the response level, with task-related conflicts being located more posterior and superior than response conflicts. A similar dissociation was found in Stroop tasks by Kim, Kroger, and Kim (2011) for perceptual versus response conflicts and by van Veen and Carter (2005) for conceptual versus response conflicts.

The finding that dissociable frontal networks responded to the two types of conflict is in accordance with recent claims that different control functions are recruited for different control demands (Egner, 2008; Egner, Delano, & Hirsch, 2007). Our data suggest that a posterior portion of the dorsal medial PFC located in the pre-SMA, along with the left DLPFC, is part of a control system that mediates the processing of interference caused by competing LTM representations of distinct stimulus domains by boosting the task-relevant associations. In contrast, a system comprising a more anterior part of the medial PFC and the DLPFC is involved in processing response conflicts. In the used paradigm, conflict arises at different levels of information processing and therefore the conflict-monitoring system receives input from different levels (i.e., from the level of LTM representations vs. from the response level), which could be the reason for why distinct areas in the medial PFC respond. In contrast, the mechanisms, as well as the focus of control (output), seem to be the same in the two conflicts: The data suggest that in both cases the task-relevant LTM representations become increasingly activated.

To conclude, this study contributes to the question of how the cognitive system deals with situations in which

different memory representations are activated by the same retrieval cue, but only one representation is task-relevant. In such situations, not only relevant, but also irrelevant associations become activated, which results in retrieval interference. This triggers control processes mediated by the pre-SMA and DLPFC, which regulate the activation pattern of LTM representations in posterior brain areas. Not only with respect to the level of information processing on which the conflict arises (level of LTM representations), this retrieval conflict is different from other conflicts, such as response conflict (arising on the response level)—There are also different neural substrates in the medial PFC involved. The found dissociation shows that multiple separable mechanisms of cognitive control become activated for different control demands.

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Reprint requests should be sent to Patrick H. Khader, Department of Psychology, Philipps-University Marburg, Marburg, Germany, or via e-mail: Khader@uni-marburg.de, or to Kerstin Jost, Institute of Psychology, RWTH Aachen University, Aachen, Germany, or via e-mail: Jost@psych.rwth-aachen.de.

Notes

1. Doubling the numbers of trials did not affect the general result pattern. An analysis of the behavioral data did not reveal any important differences between the first and second halves of the EEG session.
2. One might expect that conflict is also reflected in early ERPs. Note, however, that in any case only words were presented (as retrieval cues). Conflicts should therefore start to emerge not earlier than the retrieval of the corresponding information. Therefore, it is not to be expected for the present paradigm that early potentials, such as the N2/N200 that has been found to be sensitive for conflict (as in the flanker task; see, e.g., Wendt, Heldmann, Münte, & Kluge, 2007), show conflict-related differences. Nevertheless, we checked our data for ERP effects in the time window before 1000 msec. However, no reliable differences have been observed.

REFERENCES

- Anderson, M. C., Bjork, E. L., & Bjork, R. A. (1994). Remembering can cause forgetting: Retrieval dynamics in long-term memory. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *20*, 1063–1087.
- Anderson, M. C., Ochsner, K. N., Kuhl, B., Cooper, J., Robertson, E., Gabrieli, S. W., et al. (2004). Neural systems underlying the suppression of unwanted memories. *Science*, *303*, 232–235.
- Aron, A. R. (2007). The neural basis of inhibition in cognitive control. *Neuroscientist*, *13*, 214–228.
- Badre, D., & Wagner, A. D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia*, *45*, 2883–2901.
- Bentin, S., Allison, T., Puce, A., Perez, E., & McCarthy, G. (1996). Electrophysiological studies of face perception in humans. *Journal of Cognitive Neuroscience*, *8*, 551–565.
- Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*, 624–652.
- Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., Holyoak, K. J., et al. (2001). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. *Neuroimage*, *14*, 1136–1149.
- Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*, 332–361.
- Danker, J. F., & Anderson, J. R. (2010). The ghosts of brain states past: Remembering reactivates the brain regions engaged during encoding. *Psychological Bulletin*, *136*, 87–102.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222.
- Desmet, C., Fias, W., Hartstra, E., & Brass, M. (2011). Errors and conflict at the task level and the response level. *Journal of Neuroscience*, *31*, 1366–1374.
- Egner, T. (2008). Multiple conflict-driven control mechanisms in the human brain. *Trends in Cognitive Sciences*, *12*, 374–380.
- Egner, T., Delano, M., & Hirsch, J. (2007). Separate conflict-specific cognitive control mechanisms in the human brain. *Neuroimage*, *35*, 940–948.
- Egner, T., & Hirsch, J. (2005). Cognitive control mechanisms resolve conflict through cortical amplification of task-relevant information. *Nature Neuroscience*, *8*, 1784–1790.
- Gazzaley, A., Cooney, J. W., McEvoy, K., Knight, R. T., & D'Esposito, M. (2005). Top-down enhancement and suppression of the magnitude and speed of neural activity. *Journal of Cognitive Neuroscience*, *17*, 507–517.
- Hager, W., & Hasselhorn, M. (1994). *Handbuch deutschsprachiger Wortnormen*. Göttingen: Hogrefe.
- Heil, M., Rösler, F., & Hennighausen, E. (1996). Topographically distinct cortical activation in episodic long-term memory: The retrieval of spatial versus verbal information. *Memory and Cognition*, *24*, 777–795.
- Hennighausen, E., Heil, M., & Rösler, F. (1993). A correction method for DC drift artifacts. *Electroencephalography and Clinical Neurophysiology*, *86*, 199–204.
- Huynh, H., & Feldt, L. S. (1976). Estimation of the Box correction for degrees of freedom from sample data in randomized block and split-plot designs. *Journal of Educational Statistics*, *1*, 69–82.
- Ishai, A., Ungerleider, L. G., Martin, A., & Haxby, J. V. (2000). The representation of objects in the human occipital and temporal cortex. *Journal of Cognitive Neuroscience*, *12*, 35–51.
- Jasper, H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, *10*, 371–375.
- Kerns, J. G., Cohen, J. D., MacDonald, A. W., III, Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science*, *303*, 1023–1026.
- Khader, P., Burke, M., Bien, S., Ranganath, C., & Rösler, F. (2005). Content-specific activation during associative long-term memory retrieval. *Neuroimage*, *27*, 805–816.
- Khader, P., Heil, M., & Rösler, F. (2005). Material-specific long-term memory representations of faces and spatial positions: Evidence from slow event-related brain potentials. *Neuropsychologia*, *43*, 2109–2124.

- Khader, P., Knoth, K., Burke, M., Bien, S., Ranganath, C., & Rösler, F. (2007). Topography and dynamics of associative long-term memory retrieval in humans. *Journal of Cognitive Neuroscience, 19*, 492–511.
- Khader, P., & Rösler, F. (2009). Where memories are stored discloses how memories are formed—Content specificity of long-term memory representations. In R. Rösler, C. Ranganath, B. Röder, & R. H. Kluwe (Eds.), *Neuroimaging of human memory—Linking cognitive processes to neural systems* (pp. 283–298). Elsevier.
- Kim, C., Kroger, J. K., & Kim, J. (2011). A functional dissociation of conflict processing within anterior cingulate cortex. *Human Brain Mapping, 32*, 304–312.
- Koechlin, E., Ody, C., & Kouneiher, F. (2003). The architecture of cognitive control in the human prefrontal cortex. *Science, 302*, 1181–1185.
- Kuhl, B. A., Kahn, I., Dudukovic, N., & Wagner, A. D. (2008). Overcoming suppression in order to remember: Contributions from anterior cingulate and ventrolateral prefrontal cortex. *Cognitive, Affective, and Behavioral Neuroscience, 8*, 211–221.
- Kuhl, B. A., Rissman, J., Chun, M. M., & Wagner, A. D. (2011). Fidelity of neural reactivation reveals competition between memories. *Proceedings of the National Academy of Sciences, U.S.A., 108*, 5903–5908.
- MacDonald, A. W., III, Cohen, J. D., Stenger, V. A., & Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science, 288*, 1835–1838.
- McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology, 62*, 203–208.
- McClelland, J. L., McNaughton, B. L., & O'Reilly, R. C. (1995). Why there are complementary learning systems in the hippocampus and neocortex: Insights from the successes and failures of connectionist models of learning and memory. *Psychological Review, 102*, 419–457.
- Mecklinger, A. (1998). On the modularity of recognition memory for object form: A spatial location: A topographic ERP analysis. *Neuropsychologia, 36*, 441–460.
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*, 167–202.
- Moscovitch, C., Kapur, S., Köhler, S., & Houle, S. (1995). Distinct neural correlates of visual long-term memory for spatial location and object identity: A positron emission tomography study in humans. *Proceedings of the National Academy of Sciences, U.S.A., 92*, 3721–3725.
- Nee, D. E., Jonides, J., & Berman, M. G. (2007). Neural mechanisms of proactive interference-resolution. *Neuroimage, 38*, 740–751.
- O'Reilly, R. C., & Rudy, J. W. (2001). Conjunctive representations in learning and memory: Principles of cortical and hippocampal function. *Psychological Review, 108*, 311–345.
- Öztekin, I., & Badre, D. (2011). Distributed patterns of brain activity that lead to forgetting. *Frontiers in Human Neuroscience, 5*, 1–8.
- Picard, N., & Strick, P. L. (2001). Imaging the premotor areas. *Current Opinion in Neurobiology, 11*, 663–672.
- Polyn, S. M., Natu, V. S., Cohen, J. D., & Norman, K. A. (2005). Category-specific cortical activity precedes retrieval during memory search. *Science, 310*, 1963–1966.
- Rösler, F., Heil, M., & Röder, B. (1997). Slow negative brain potentials as reflections of specific modular resources of cognition. *Biological Psychology, 45*, 109–141.
- Souza, M. J., Donohue, S. E., & Bunge, S. A. (2009). Controlled retrieval and selection of action-relevant knowledge mediated by partially overlapping regions in left ventrolateral prefrontal cortex. *Neuroimage, 46*, 299–307.
- Sporer, S. L. (1999). *The own-race bias in Germany: Testing the contact hypothesis with Turks and Germans*. Paper presented at the 4th European Conference on Psychology and Law of the American Psychology-Law Association and the European Psychology-Law Association in Dublin, Ireland.
- Talairach, J., & Tournoux, P. (1988). *Co-planar stereotaxic atlas of the human brain*. Stuttgart: Thieme.
- Underwood, B. J. (1957). Interference and forgetting. *Psychological Review, 64*, 49–60.
- van Veen, V., & Carter, C. S. (2005). Separating semantic conflict and response conflict in the Stroop task: A functional MRI study. *Neuroimage, 27*, 497–504.
- Wendt, M., Heldmann, M., Münte, T. F., & Kluwe, R. H. (2007). Disentangling sequential effects of stimulus- and response-related conflict and stimulus-response repetition using brain potentials. *Journal of Cognitive Neuroscience, 19*, 1104–1112.
- Wimber, M., Bäuml, K. H., Bergström, Z., Markopoulos, G., Heinze, H. J., & Richardson-Klavehn, A. (2008). Neural markers of inhibition in human memory retrieval. *Journal of Neuroscience, 28*, 13419–13427.