

The Interrelations between Verbal Working Memory and Visual Selection of Emotional Faces

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Abstract

■ Working memory (WM) and visual selection processes interact in a reciprocal fashion based on overlapping representations abstracted from the physical characteristics of stimuli. Here, we assessed the neural basis of this interaction using facial expressions that conveyed emotion information. Participants memorized an emotional word for a later recognition test and then searched for a face of a particular gender presented in a display with two faces that differed in gender and expression. The relation between the emotional word and the expressions of the target and distractor faces was varied. RTs for the memory test were faster when the target face matched the emotional word held in WM (on valid trials) relative to when the emotional word matched the expression of the distractor (on invalid trials). There

was also enhanced activation on valid compared with invalid trials in the lateral orbital gyrus, superior frontal polar (BA 10), lateral occipital sulcus, and pulvinar. Re-presentation of the WM stimulus in the search display led to an earlier onset of activity in the superior and inferior frontal gyri and the anterior hippocampus irrespective of the search validity of the re-presented stimulus. The data indicate that the middle temporal and prefrontal cortices are sensitive to the reappearance of stimuli that are held in WM, whereas a fronto-thalamic occipital network is sensitive to the behavioral significance of the match between WM and targets for selection. We conclude that these networks are modulated by high-level matches between the contents of WM, behavioral goals, and current sensory input. ■

INTRODUCTION

Previous studies show that visual selection is biased to stimuli matching the contents of the working memory (WM), even when WM content is irrelevant for visual selection (Chanon & Hopfinger, 2008; Olivers, Meijer, & Theeuwes, 2006; Soto, Humphreys, & Heinke, 2006; Soto, Heinke, Humphreys, & Blanco, 2005; Downing, 2000; for recent reviews, see Olivers, 2008; Soto, Hodsoll, Rotshtein, & Humphreys, 2008). The interaction between WM and visual selection is often discussed in terms of the biased competition model (Desimone & Duncan, 1995). According to this model, neural representations of different objects in a visual scene compete against each other in a mutually inhibitory fashion to gain access to higher level processing and awareness. This competition is modulated by the top-down activation of object features from representations held in WM, which biases neural activity to favor stimuli with matching features. Supportive data come from both single-cell recording studies (Chelazzi, Miller, Duncan, & Desimone, 1993) and from human studies using fMRI (Soto, Humphreys, & Rotshtein, 2007; Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998). For example, holding spatial locations in WM leads to increased responses in associated representations

in early visual cortex (Postle, Awh, Jonides, Smith, & D'Esposito, 2004).

Although in most studies the information held in WM is directly related to the task goals, there is also evidence that WM can affect attention even if the information is irrelevant to the task. For example, attention can be drawn to a stimulus in WM even if this stimulus always cues a distractor rather than a target in a subsequent search task (Olivers, 2008; Olivers et al., 2006; Soto et al., 2005, 2006; Downing, 2000), and this match between the WM and a search display influences the fastest RTs in search and the first saccades that are made (Soto et al., 2005, 2006). Soto et al. (2007) explored the neural basis of these effects using fMRI. They reported two distinct activation patterns. First, reappearance of a WM item in a search display increased neuronal responses in the parahippocampal, superior frontal, and lingual gyri. This occurred irrespective of whether the WM stimulus was valid (cueing the search target) or invalid (cueing a distractor) in the search display. These regions were sensitive to any match between the new search display and the representations in WM. A second activation pattern was observed in a frontal-pulvinar network and was sensitive to the validity of the match between the WM and the search targets. There were increased responses when the WM item matched the target for the search task and decreased responses when the WM item matched a search distractor.

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This frontal-pulvinar network was thus influenced by the overlap between the WM representation and the representation of the search goals. Increasing activation, on valid trials, may facilitate response initiation; suppression of activation, on invalid trials, may slow response initiation.

Soto et al. (2007) also included a further condition in which a first stimulus had to be identified but not held in WM, before the search display occurring. This assesses effects from bottom-up processing of the initial item. Although this condition is visually matched to the WM condition, it typically exerts a much smaller behavioral effect (Soto et al., 2005). The imaging data indicated that, rather than there being increased activation from representation of the initial item in the search display (the finding under WM conditions), there was reduced activation in areas overlapping those activated in the WM condition. This is consistent with a form of passive adaptation to the cue, which seems to be overridden under WM conditions. The results indicate that the neural response differs under WM and bottom-up priming conditions, confirming the critical role of WM in generating the effects.

An influential model of WM (Baddeley, 1993) suggests that WM is composed of several content-specific subsystems, including a verbal phonological loop, a visuospatial sketchpad, and even an abstract “episodic” codes that integrate representations from different modality-specific systems (Baddeley & Hitch, 2000; Thompson & Paivio, 1994; Paivio & te Linde, 1980). In line with this, recent behavioral evidence has shown that a verbal WM item (“e.g., pink circle”) can draw attention automatically to a matching visual stimulus in a search display (Huang & Pashler, 2007; Soto & Humphreys, 2007). Similarly, it was shown that semantic association between WM and search display affect selection and memory processes (Belke, Humphreys, Watson, Meyer, & Telling, 2008; Moores, Laiti, & Chelazzi, 2003). However, it is unclear whether the neural basis of this effect of matching abstract information is the same as the neural basis of effects stemming from visual representations in WM (Soto et al., 2007). In addition, we do not know whether effects of matching are contingent solely on descriptions of the physical properties of a stimulus (“pink circle”) or whether they may also be mediated by descriptions of abstract mental states (e.g., “happy” or “fear”) of more naturalistic stimuli.

Note that a crucial aspect of the WM search paradigm is that memory and search are manipulated in an orthogonal fashion (Soto et al., 2007). Therefore, in the current experiment, we chose to work with emotion and facial expressions. Faces have orthogonal conceptual attributes (gender, age, expression, race, etc.) that are easily recognizable. This is ideal to vary semantic associations between memory and search display independently. It is difficult to think of any other biological stimuli that share the same property, that is, multiple orthogonal features within the same object category. This enabled us to use a verbal description of one feature (i.e., emotion) for the

WM item while performing a search task on an orthogonal feature, that is, gender.

In the current study, we tested whether an overlap between the description of an abstract emotional state and a subsequent search display could modulate visual attention and whether any modulation involved brain regions identified in the interaction between visual WM and search (Soto et al., 2007). We used descriptions of emotional states (e.g., fearful, joyful, neutral), which had to be held in WM while participants searched a subsequent display for a face of a particular gender (localize the female/male face). The faces in the search task expressed different emotional states (e.g., fearful, joyful, neutral), and the descriptor in WM matched the emotional state of the target on one third of the trials (valid trial) and the emotional state of the distractor on another third (invalid trials) or neither on the remaining trials (baseline).

On the basis of prior behavioral studies, we predicted that RTs to the target should be facilitated when the emotional content of the word in WM matched the target’s expression (on valid trials), whereas it would be disrupted when it matched the expression of the distractor face (on invalid trials). In addition, previous work has shown that WM is impaired if attention is distracted from a stimulus in a memorized location (Awh & Jonides, 2001; Awh, Jonides, & Reuter-Lorenz, 1998). Hence, we also predicted that the validity of the emotional cue in relation to the target face may affect memory for the emotional cue. Both results would be consistent with attention being drawn to the stimulus in the search display whose emotional expression matched that of the WM stimulus. If the neural circuits mediating the effects of WM on selection are common across matches based on abstract emotional descriptors (as here) and visual WM stimuli (as in Soto & Humphreys, 2007), then we expect (i) the regions of frontal, medial-temporal, and visual cortex to respond to the reoccurrence of the WM stimulus in the search display irrespective of its validity (parahippocampal, superior frontal, and lingual gyri) and (ii) the activation in a frontal-pulvinar network to reflect the interaction between the search target and the reappearing WM stimulus (an effect of cue validity).

METHODS

Participants

Twelve right-handed, native English-speaking women (age range = 20–29 years) participated in the experiment. All were naive to the purpose of the experiment. None had a history of any neurological or psychiatric disorders, and their vision was normal or corrected to normal. Due to shimming problems, during the acquisition of the fMRI data, two participants were removed from the fMRI analysis. The study was approved by the local ethics committee.

Stimuli

Verbal descriptions of emotional states were used as WM stimuli. There were three emotional states: fear, happy, and neutral. Each state was described by two different words: fear—“fearful,” “afraid”; neutral—“neutral,” “indifferent”; happy—“happy,” “joyful.” Three native English speakers confirmed that the content of each word matched the specific emotional state. WM cues were words presented at fixation, written in capital letters using Arial font size 44 pt. In the WM test, two flanker words (7.4° visual angle from fixation) were presented at a time, one depicting the WM item and the other was a distracter. The memorized word was randomly assigned to the left or to the right of the screen, and it could appear with any other word that depicted a different emotional state. The words were written in small letters using Arial font size 38 pt. The word font and spatial locations were changed from the cue to the test displays to ensure that the memory was not based on visual overlap and to avoid perceptual priming.

In the search task, we used facial expressions taken from the standardized NimStim set (Tottenham et al., in press). Forty-two identities (21 women) of mixed ethnic origins that had the most recognizable expressions of fearful, happy, and neutral were used. Each search display depicted two flanker faces of different genders and each with a different expression. The faces were randomly paired. Stimuli size were 3.52° (500 × 610 pixels), and the distance of the center of each flanker from fixation was 7.4°.

There were two words for each emotional state and 42 face identities for each expression. This ensured that there was no one-to-one matching between the content of WM and the facial expressions. Thus, association between the WM content and the search display could only be made after each stimulus had been processed and semantically coded.

Procedure

In the WM task, observers were asked to memorize the exact word for a later recognition test that was performed at the end of each trial. In the search task, half of the observers were asked to search for a female face and the other half for a male face. Note that the emotional expression of the face was entirely irrelevant for the search task. There were three conditions reflecting the relations between the WM item and the search target: (a) valid (the emotional state described by the WM stimulus matched the expression of the target face in the search task); (b) invalid (the emotion state expressed by the WM matched the expression of the distracter); and (c) a baseline condition, where the descriptor held in WM did not match any expression in the search display. Importantly, across the three conditions, the visual displays were identical.

Each trial began with a fixation display for 0.5 sec to alert the observer of the beginning of the trial. Then a verbal memory cue appeared for 1 sec followed by a 1-sec blank interval with a fixation cross. The search display with the two flanker faces appeared next for 0.5 sec. The observer’s task was to detect the position (left or right) of the female (or male for half the participants) face by pressing a left or a right response key. Following the offset of the search items, there was a 1-sec blank interval, which was followed by the memory recognition test. Here, two flanker words appeared for 1 sec, and the task was to indicate the position of the memorized word (left or right; Figure 1A). The location of the different stimuli was randomized. The total length of a trial was 5 sec. A jittered interval was implemented between trials ranging from 2 to 4.5 sec to facilitate estimation of BOLD response to each event.

Participants were instructed to maximize performance (speed and accuracy) on both tasks and to maintain fixation at a plus symbol placed at the center of the display throughout the experiment. Before scanning, the observers were familiarized with the task and performed one practice block of 27 trials. The experiment was divided to six sessions of 27 trials each. Cue validity varied randomly across trials. This gave a total of 54 trials per condition with an equal balance of the emotionality of the WM item, of the search target, and of the distracter. Stimuli were presented using E-prime (Psychology Software Tools, Pittsburgh, PA).

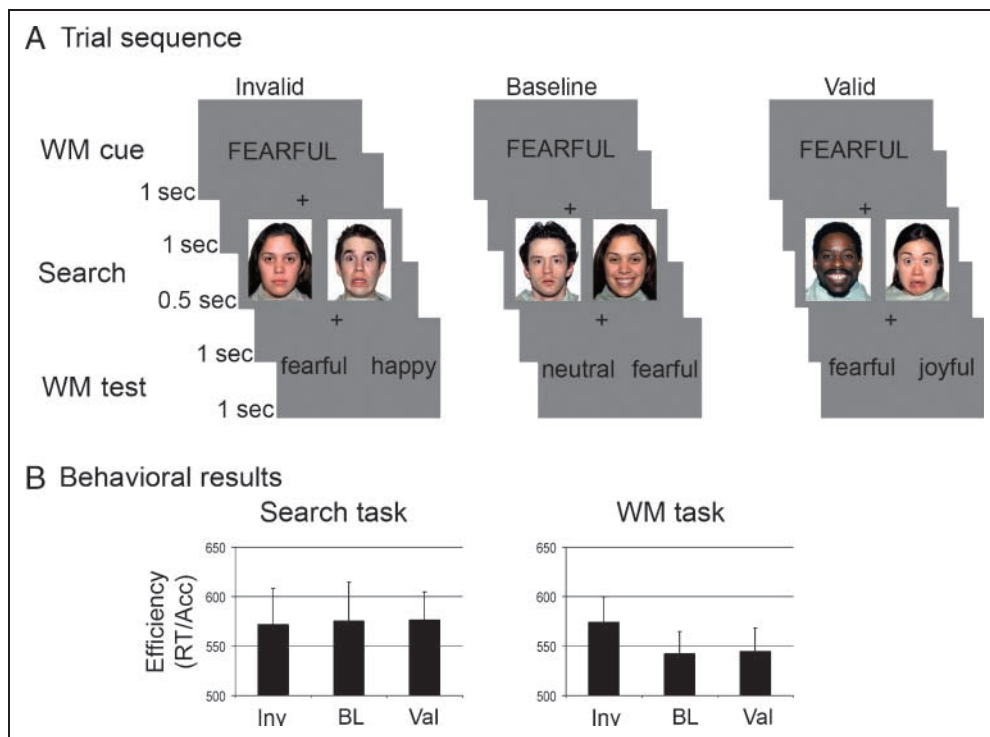
fMRI Data Acquisition

We used a Phillips 3-T Achieva system to acquire BOLD contrast-weighted EPI for the functional scans. Thirty-two oblique slices, 2-mm thickness with a 1.25-mm gap, were acquired, resulting in an in-plane resolution of 2 × 2 × 3.25 mm, with 80° flip angle, 35 msec echo time, and 2050 msec slice repetition time. Images were acquired using an eight-channel phase array coil with a sense factor of 2. To minimize susceptibility artifacts, shimming was performed for each acquisition run and slices were tilted 30° along the frontal-temporal cortex (Deichmann, Gottfried, Hutton, & Turner, 2003). The slices covered most of the brain, including the entire temporal cortex but excluding the most posterior-superior bit of the parietal cortex and anterior-inferior parts of the cerebellum.

Data Analysis

Behavioral responses in the search and the WM tasks (performed during the fMRI experiment) were analyzed using SPSS15.00 and Matlab. The median RTs for correct responses, the percentage accuracy data (Acc), and the search efficiency (RT/proportion of accurate responses; Townsend & Ashby, 1983) were compared separately for the WM and the search task. Statistical inferences

Figure 1. Experimental design and behavioral results. (A) Examples of the trial sequence: three trial types are presented—invalid, baseline, and valid—for the verbal WM cue “fearful.” (B) Behavioral results are presented here in terms of processing efficiency (RT/proportion of accurate responses) for the search and memory tasks.



were made using repeated measures one-way ANOVA with the conditions invalid, baseline, and valid. Significance levels were adjusted using Greenhouse–Geisser correction to account for sphericity effects in the data.

The fMRI data were analyzed using SPM5 (Wellcome Department of Imaging Neuroscience, London; www.fil.ion.ucl.ac.uk/spm). In preprocessing of the data, the EPI volumes were spatially realigned to correct for movement artifacts (Ashburner & Friston, 2003a) and motion by distortions interactions (Andersson, Hutton, Ashburner, Turner, & Friston, 2001), transformed to the Montreal Neurological Institute standard space (Ashburner & Friston, 2003b), and smoothed using 9-mm Gaussian kernel to account for residual intersubject differences and to accommodate assumptions of random field theory used for family-wise error corrections (Worsley & Friston, 1995).

For statistical analysis, we first estimated the effect size for each participant on each of the three conditions averaged across the six sessions using the general linear model (Kiebel & Holmes, 2003). We modeled only events in which correct responses were given for both the search and the WM tasks. Error trials were modeled separately. Because our main question related to the interaction between WM and selection, activation onsets were aligned with the appearance of the search display. Apart of the regressors for the onsets of each condition, we added the following covariates: the emotionality of the WM word, the emotionality of the target’s expression, and the RTs for the search and the WM tasks. The emotion-related covariates depicted linear [(1) happy, (0) neutral, (–1) fear] and quadratic [(1) happy, (0) neutral, (1) fear] effects. All regressors were convolved with two basis function: the ca-

nonical hemodynamic response function (cHRF; Friston, Glaser, Mechelli, Turner, & Price, 2003) and its time derivatives (TDerv) that capture fluctuations in response onset (Friston et al., 1998). To correct for signal changes due to head movement, the six realignment parameters were included in the design matrix. An additional set of harmonic regressors was used to account for any low frequency temporal variance within the data, which is typical of fMRI signal with a cutoff of 1/128 Hz.

Consistent effects across subjects (random-effects, second-level analysis; Penny, Holmes, & Friston, 2003) were then tested using a model depicting the estimated cHRF and TDerv effects of the three experimental conditions (invalid, baseline, and valid). In this model, we did not assume independency or equal variance between the conditions. The derivatives were included in the model to test the differences in the response shape function with regard to the onset time, peak time, and amplitude between the conditions. These were tested using *F* tests. Plots of the estimated response are a summation of the effects (β) of the basis functions used: [$\beta_1 \times \text{cHRF} + \beta_2 \times \text{TDerv}$]. The plots and the simple effects are computed on the responses (the first eigen variant) of a 3-mm³ sphere centered on the maxima group response. For cortical structures, we reported clusters at *p* < .001 uncorrected that were larger than 30 mm³, unless specified otherwise.

For descriptive purposes, we also estimated a general linear model for each participant where we used finite impulse response (FIR) functions to model the response for each condition. The FIR functions were 2 sec binned for a 16-sec peristimulus duration and aligned with the onset of the WM cue. The FIR base functions do not

assume any specific HRF response shape and estimate the effect size at each time bin separately. We plotted the averaged FIR across participants extracted from maxima peaks obtained from the previous analysis in the ROIs.

Note that the main aim of the current study was to test interactions between WM and visual selection processes, and the emotionality of stimuli was used to manipulate irrelevant, abstract relations between the WM and the search stimuli. Consequently, we did not analyze neural or behavioral effects of specific emotional contexts (e.g., fear vs. happy).

RESULTS

Behavioral Data

We computed separate repeated measures ANOVAs for the memory and the visual selection tasks for each of the three measures: RT, accuracy, and efficiency (results for the efficiency measure are presented in Figure 1B; see Supplementary Table 1). Overall, accuracy was high in both the search task (96.3%, $SEM = 0.01\%$) and the memory test (96.7%, $SEM = 0.008\%$), indicating that observers had no difficulty following task instructions. There were no significant effects of the WM stimulus on the search task: RT, $F(1.8, 19.8) = 0.13$, $p = .87$, partial eta squared ($p\eta^2$) = .012; Acc, $F(1.7, 18.8) = 0.4$, $p = .6$, $p\eta^2 = .03$; efficiency, $F(1.4, 15.6) = 0.12$, $p = .8$, $p\eta^2 = .01$. This result suggests that the contents of WM did not affect responses on the gender search task. However, the relation between the selection and the WM tasks affected performance in the WM task. Memory was impaired when the distracter's expression matched the item in the WM (invalid) compared with when the WM matched the target's expression in the valid condition: RT, $F(1.6, 17.5) = 5.4$, $p = .01$, $p\eta^2 = 0.332$; Acc, $F(1.8, 20.1) = 6$, $p = .01$, $p\eta^2 = 0.35$; efficiency, $F(1.7, 19.4) = 10.7$, $p = .001$, $p\eta^2 = 0.49$. Comparison across the conditions suggested that this effect was driven by the cost of a search distractor matching the content of WM (invalid vs. baseline), efficiency, $t(11) = 4.4$, $p = .03$, $\eta^2 = 0.61$, rather than there being a benefit when the search target matched the contents of WM (valid vs. baseline), efficiency, $t(11) = 0.676$, $p = .51$. To explain the memory data, we proposed that interference in WM arose on invalid trials because there was suppression of the distractor face (including the associated emotional expression) to select the target face. On invalid trials, this meant that there was suppression of the emotional state linked to the WM cue, and this disrupted the maintenance of the emotional word in memory. This is consistent with WM and visual selection sharing common processes at a relatively abstract level, so that suppression of facial expression leads to suppression of an associated emotional state in WM. The lack of effect of the WM cue on search, however, suggests that the guidance of search by facial gender (the target defini-

tion) was stronger than guidance by the emotional descriptor held in WM (for further details, see Discussion).

fMRI Data

We first tested for regions that showed an amplitude change during the search task (using the F contrast—invalid, baseline, and valid—the contrast was 1 0 0; 0 1 0; and 0 0 1, respectively). This contrast tested for any region that showed a significant difference in responses from zero for any of the conditions (invalid/baseline/valid). Note that this general contrast includes regions responding to the visual stimuli (stimuli vs. fixation), regions involved in generating the motor response, and regions that are involved in nonspecific task demands. Given the nonspecificity of this contrast, we reported only results that survive whole-brain family-wise error correction ($p < .05$). Regions showing a significant response to any of the condition are presented in Table 1 and Figure 2.

As expected, we observed strong responses (i) in the occipital cortex associated with the visual stimuli; (ii) in the superior temporal gyrus associated with processing emotional stimuli; (iii) in the intraparietal and superior frontal sulci associated with the WM and the attentional demands of the task; and (iv) in the central sulcus, the precentral sulcus, and the cerebellum associated with action and motor responding. Interestingly, neural responses in all these regions also reflected the relation between the emotionality of the WM word and the target's expression: There was an increased response when the emotionality of the WM word matched the target's expression compared with when it matched the distracter's expressions. The reliability of this observation (valid > invalid) was confirmed using two-tailed paired t test on the parameter estimates extracted from left inferior occipital gyrus, $t(9) = 6.9$, $p < .001$, $\eta^2 = 0.82$, left superior temporal gyrus, $t(9) = 2.4$, $p = .04$, $\eta^2 = 0.36$, and left central sulcus, $t(9) = 2.9$, $p = .015$, $\eta^2 = 0.45$.

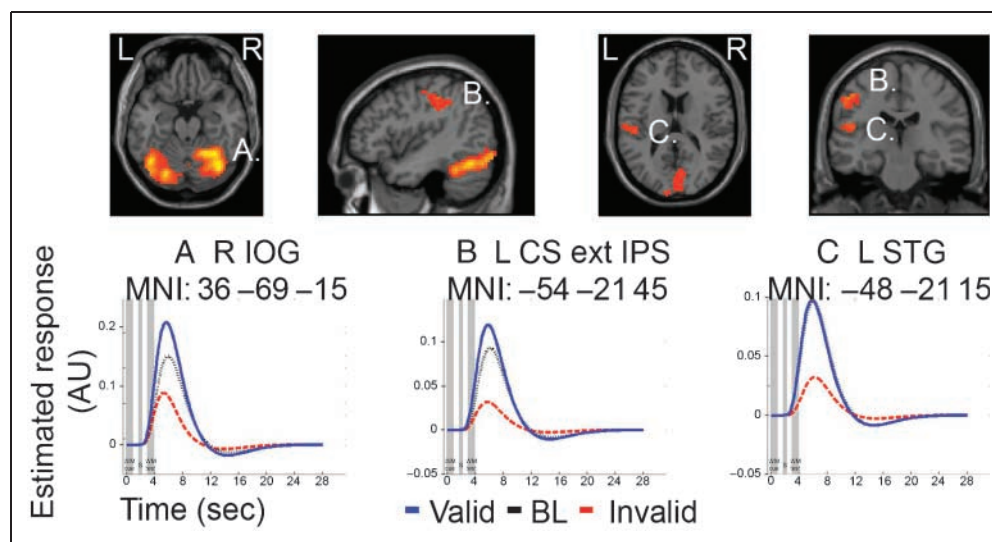
We next tested more directly neural responses that reflected the interaction between WM and attention (i.e., the relations between the emotionality of the WM word and the target's expression). This was done by comparing responses to valid versus invalid trials (valid > baseline > invalid). Note that this contrast, as opposed to the F contrast reported above, controls for general effects of stimuli, tasks, and motor responses because the different validity conditions were identical in terms of the search stimuli presented, the task, and the motor response requirements. Thus, any effect observed will reflect only processes involved in the interaction between WM and selection. The results replicated Soto et al. (2007) in that there were increased responses to valid trials and decreased responses to invalid trials compared with the baseline in the bilateral pulvinar and anterior frontal polar cortex (BA 10). This replication occurred despite the marked differences across these studies in stimuli, the nature of the overlap between the WM and the search

Table 1. Main Effect of Amplitude Change in Any of the Conditions, *F* contrast (family-wise error [FWE], *p* < .05)

Anatomy	BA	η^2	Z	MNI (x, y, z)
<i>Occipital</i>				
IOG	19	0.98	Inf	36 -69 -15
4thOG	18	0.97	Inf	-18 -81 -15
SOG	18	0.77	4.77	27 -90 30
SOG	19	0.85	5.45	-27 -81 21
MOG	19	0.83	5.20	-45 -78 9
<i>Temporal</i>				
STG	48	0.88	5.77	-48 -24 15
<i>Fronto-Parietal</i>				
CS ext IPS	3	0.93	6.59	-54 -21 45
preCS	6	0.81	5.01	-57 6 18
preCS	6	0.79	4.90	-60 6 30
SFS	6	0.85	5.42	-27 -6 54
CG	24	0.89	5.93	-3 9 45
<i>Subcortical</i>				
Cerebellum		0.80	5.00	3 -66 -24
Cerebellum		0.79	4.90	0 -75 -39
Cerebellum		0.78	4.81	3 -78 -36
Pulvinar		0.80	4.94	-12 -21 6

BA = Brodmann's area; η^2 = a measure of effect size; IOG = inferior occipital gyrus; 4thOG = fourth occipital gyrus; CS = central sulcus; IPS = intraparietal sulcus; CG = cingulate gyrus; STG = superior temporal gyrus; SOG = superior occipital gyrus; SFS = superior frontal sulcus; MOG = middle occipital gyrus; preCS = inferior precentral sulcus; ext = extend to.

Figure 2. Responses during WM and search task. Significant activations (family-wise error [FWE]-corrected, *p* < .05) that were revealed using an *F* contrast that tested changes in BOLD response in any or all of the three conditions (valid, baseline, and invalid) relative to fixation. Bottom row: examples of estimated HRF responses from a sample of the above regions. (A) Responses of the right inferior occipital gyrus (R IOG); (B) responses of the left central sulcus extended to intraparietal sulcus; and (C) responses of the left superior temporal gyrus (L STG).



stimuli, and the search task (e.g., emotional words vs. simple geometric shapes; faces vs. line targets), and the time sequence of the trials.

We also observed additional regions that showed a similar effect of validity, including the lateral orbital frontal cortex bilaterally, the head of the caudate, and the lateral occipital sulcus (Figure 3, Table 2). Recruitment of these latter regions may be related to the nature of the stimuli used here, and they may reflect the potential emotional and motivational relevance of the stimuli to individuals (compared with the simple geometric shapes; Soto et al., 2007). In line with our previous study (Soto et al., 2007), we did not observe any above-threshold activation where responses increased on invalid compared with valid trials.

Finally, we assessed the brain regions responding to the match between the WM cue and the occurrence of a face with a matching emotional expression (the reappearance effect), irrespective of whether the matching emotion fell on the search target or a distractor [(valid + invalid) / 2 vs. baseline]. We did not observe any above-threshold changes (increase or decrease) in the amplitude of the signal that reflected this pattern. However, we observed that there were differences in the timing and shape of the hemodynamic response function (HRF). Differences in shape of the HRF response were tested using an *F* test, where the reappearance effect was computed on the parameter estimates of the cHRF and on estimates of the TDerv. Interestingly, the interaction between the emotionality of the word held in WM and the expressions in the search display modulated the HRF shape in the anterior hippocampus and inferior and superior frontal gyrus. This effect was driven by differences in the onset of responses in the invalid and valid conditions compared with baseline (Figure 4, Table 3, and Supplementary Figure 2), where response onsets in the baseline trials were delayed compared with the responses to valid and invalid conditions. This pattern was reflected by the size of the derivative estimates, with the derivative of valid and invalid showing a

positive value (i.e., an earlier response relative to cHRF) and the derivative of the baseline condition showing a negative value (i.e., a delayed response relative to cHRF). We further plotted estimated FIR responses at these clusters. Recall that FIR basis functions do not assume any specific HRF shape. As it can be clearly seen in Figure 4, the peak response during the baseline condition was much delayed compared with the peak response of the invalid and valid trials. The data indicate that a memory trace of the emotionality of the word held in WM affected the processing of incoming sensory input by modulating the onset and the time to peak of the neural response in recognition memory systems (superior frontal gyrus, inferior frontal gyrus, and anterior hippocampus). It is also worth noting that while the onset and the peak time reflected the interaction between the WM and the sensory input, the amplitude of the response (the estimate of cHRF size) reflected the interaction between the WM and the visual selection tasks, showing larger responses to the valid than the invalid

conditions. Again, the reliability of these later observations (valid > invalid) was confirmed using two-tailed paired *t* tests on the extracted estimation of effect size: left superior frontal gyrus, $t(9) = 2.9$, $\eta^2 = 0.45$, $p = .016$; left inferior frontal gyrus, $t(9) = 3.1$, $\eta^2 = 0.49$, $p = .012$; anterior hippocampus, $t(9) = 1.9$, $\eta^2 = 0.26$, $p = .08$. Here, reappearance of an expression that matched the emotionality of the word held in WM led to earlier responses, but the magnitude of the activation then varied as a function of whether the WM stimulus (the emotion) matched the target for the search task (the target gender); there was greater activation when the WM stimulus and the search target matched.

DISCUSSION

We demonstrated interactions between WM and visual selection under conditions where there was only a semantic

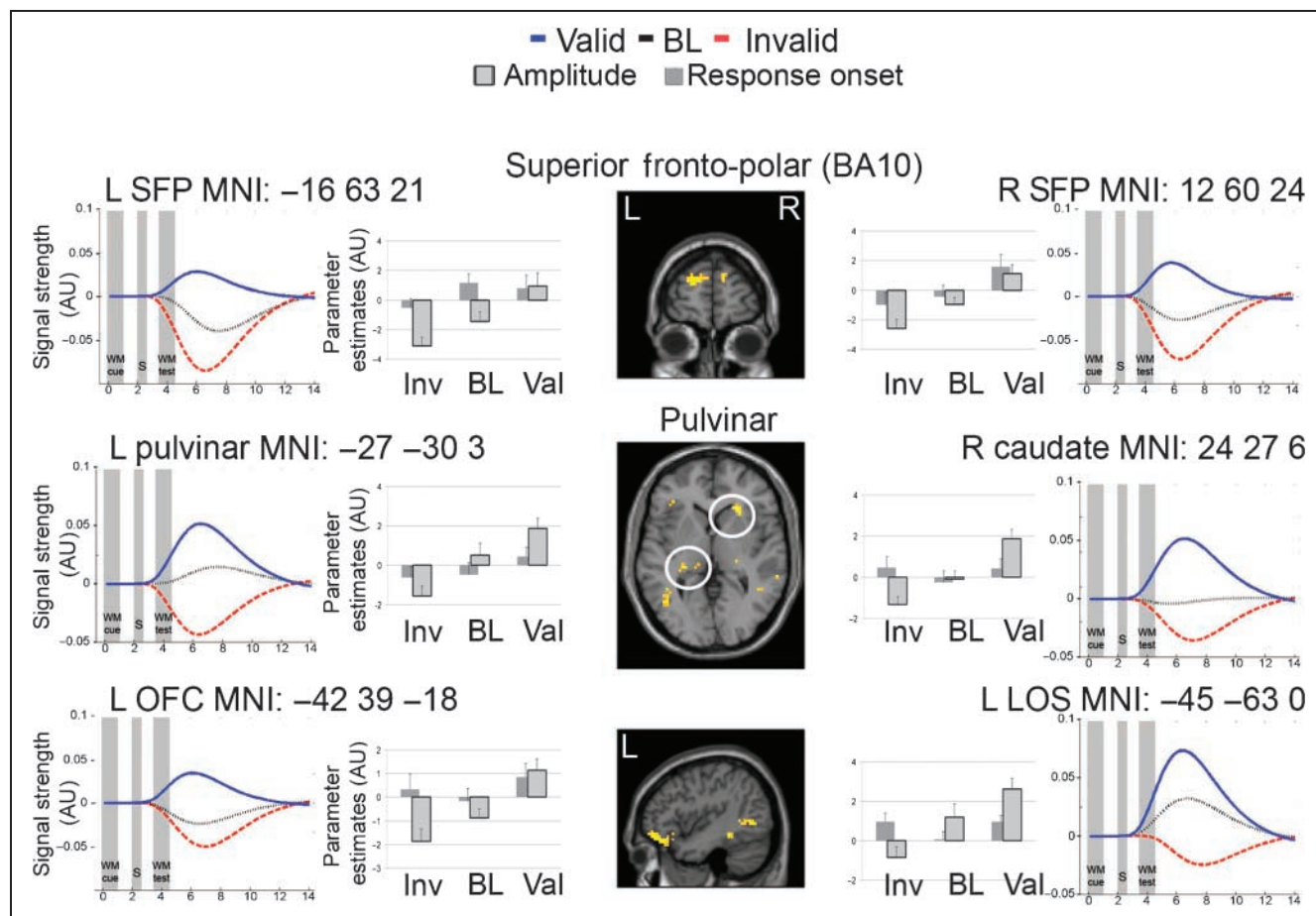


Figure 3. Interaction of the WM and search tasks' goals, effect on signal strength. Effects of validity showing increased responses to valid and decreased responses to invalid trials, when compared with baseline trials. For presentation purposes, effects are presented at $p < .005$, uncorrected and overlaid on the T1 canonical template of SPM5. The time course of the estimated HRF response ($[\beta_1 \times \text{cHRF} + \beta_2 \times \text{TDerv}]$, see Methods) extracted from the peak clusters (most left and right column). Gray bars indicate the time of different events in the trial. The bar plots (second and fourth column) represent the size of the beta values, light gray represents the cHRF, and dark gray represents the TDerv. The blacked-out line of the bars emphasizes the betas that were most informative to that contrast; in this comparison, betas of the cHRF were more informative. L = left; R = right; sFP = superior frontal polar (BA 10); OFC = orbital frontal cortex; LOS = lateral occipital sulcus; Inv = invalid; BL = baseline; V = valid; S = search task.

Table 2. Validity Effects of Amplitude: Valid > Baseline > Invalid

Anatomy	BA	η^2	Z	MNI (x, y, z)
<i>Frontal</i>				
LOFG	47	0.76	4.84 ^a	42 51 -15
LOFG ^a	47	0.68	4.03	-42 39 -18
supFP	10	0.66	3.90	-18 63 21
supFP ^b	10	0.61	3.54	12 60 24
supFP	10	0.59	3.40	-9 45 42
IFG	47	0.65	3.82	57 33 -9
<i>Temporal</i>				
STS ^b	21	0.61	3.55	45 -51 6
pSTS ^b	39	0.60	3.49	-57 -57 24
STS ^b	22	0.58	3.40	63 -39 3
pSTS ^b	39	0.63	3.35	60 -57 21
aTP	20	0.68	4.08	48 -6 -45
aTP ^b	20	0.55	3.15	-42 -3 -42
ITG	37	0.65	3.81	-45 -39 -12
<i>Occipital-Parietal</i>				
POF	7	0.64	3.76	-12 -57 33
LOS	37	0.67	3.95	-45 -63 0
CG	24	0.64	3.76	-6 6 27
pCG ^a	30	0.66	4.18	-9 -45 15
<i>Subcortical</i>				
Pulvinar ^b		0.61	3.55	-27 -30 3
Pulvinar ^b		0.58	3.35	24 -24 0
Pulvinar ^b		0.55	3.15	-15 -30 3
Caudate ^a		0.71	4.32	24 27 6
Amyg/aHipp		0.64	3.73	36 -3 -24
Pones ^a		0.78	5.06 ^a	-15 -33 -39
Cerebellum ^a		0.68	4.05	21 -81 -51
Cerebellum		0.66	3.93	24 -42 -48
Cerebellum		0.66	3.91	0 -75 -39
Cerebellum		0.61	3.55	-15 -90 -42

LOG = lateral orbital gyrus; pCG = posterior cingulate gyrus; aTP = anterior temporal pole; LOS = lateral occipital sulcus; supFP = superior fronto-polar gyrus; IFG = inferior frontal gyrus; ITG = inferior temporal gyrus; CG = cingulate gyrus; POF = parietal-occipital fissure; Amyg = amygdala; STS = superior temporal sulcus; pSTS = posterior STS.

^aFWE-corrected.

^bCluster smaller than 30 mm³.

association between stimuli in WM and the items in a subsequent search task. Note that, under these conditions, any bottom-up priming from physical similarity between the WM stimulus and the search array is minimized. Despite this, memory for the WM item was affected by the relation between the remembered word and whether it matched a target or a distractor in the search display (Figure 1B). The fMRI data further indicated a general trend that characterized the response of several brain regions in the task (Figures 2–4). Valid trials showed larger responses than invalid trials. This pattern was most pronounced in the pulvinar, BA 10, laterals OFC, caudate, and left lateral occipital sulcus (Figure 3), but it was also observed in early visual cortex and left CS regions that were associated with general visual and motor processes during the task (Figure 2). Finally, differences in peak time and response onset time of medial-temporal and prefrontal cortices were affected when a search item matched the WM stimulus, irrespective of whether this match was with a target or a distractor in the search display (i.e., irrespective of the validity of the WM stimulus).

These findings are consonant with the previous literature (Soto et al., 2007) by suggesting two levels of interactions between WM and selection processes. One level represents the interaction between WM and the processing of incoming sensory information (the overall effects of reappearance), whereas the second level represents an interaction between the WM and the goal of the subsequent selection task (the cue validity effect). We propose that the reappearance effect reflects the reactivation of memory representations of the WM stimulus and the influence of this activation on linked brain regions. In contrast, the effects of cue validity reflect the congruence between the WM and the search task set, which enhances activation when a match occurs (on valid trials) and suppresses it when memory activation conflicts with activation from the search task set (on invalid trials). This suppression effect may reflect the influence of executive control processes, which seek to modulate performance based on the task goals rather than irrelevant representations held in WM.

In this study, we did not find behavioral effects of cue validity on the search task, although effects emerged on memory performance. It is possible that categorizing face gender (required for the visual selection task) can be carried out with minimal demands on visual selection, so decisions can take place even if a distractor face is selected (e.g., when it matches the emotion referred to by the item held in WM). As a consequence, effects on search performance are difficult to observe. Other evidence indicates that memory-based guidance reduces under conditions where there is a high perceptual or cognitive load—for example, when RTs to find targets are prolonged (Han & Kim, 2009), when the search task involves varied mapping of targets (Olivers, 2008), and when the WM load increases (for a review, see Soto et al., 2008). Hence,

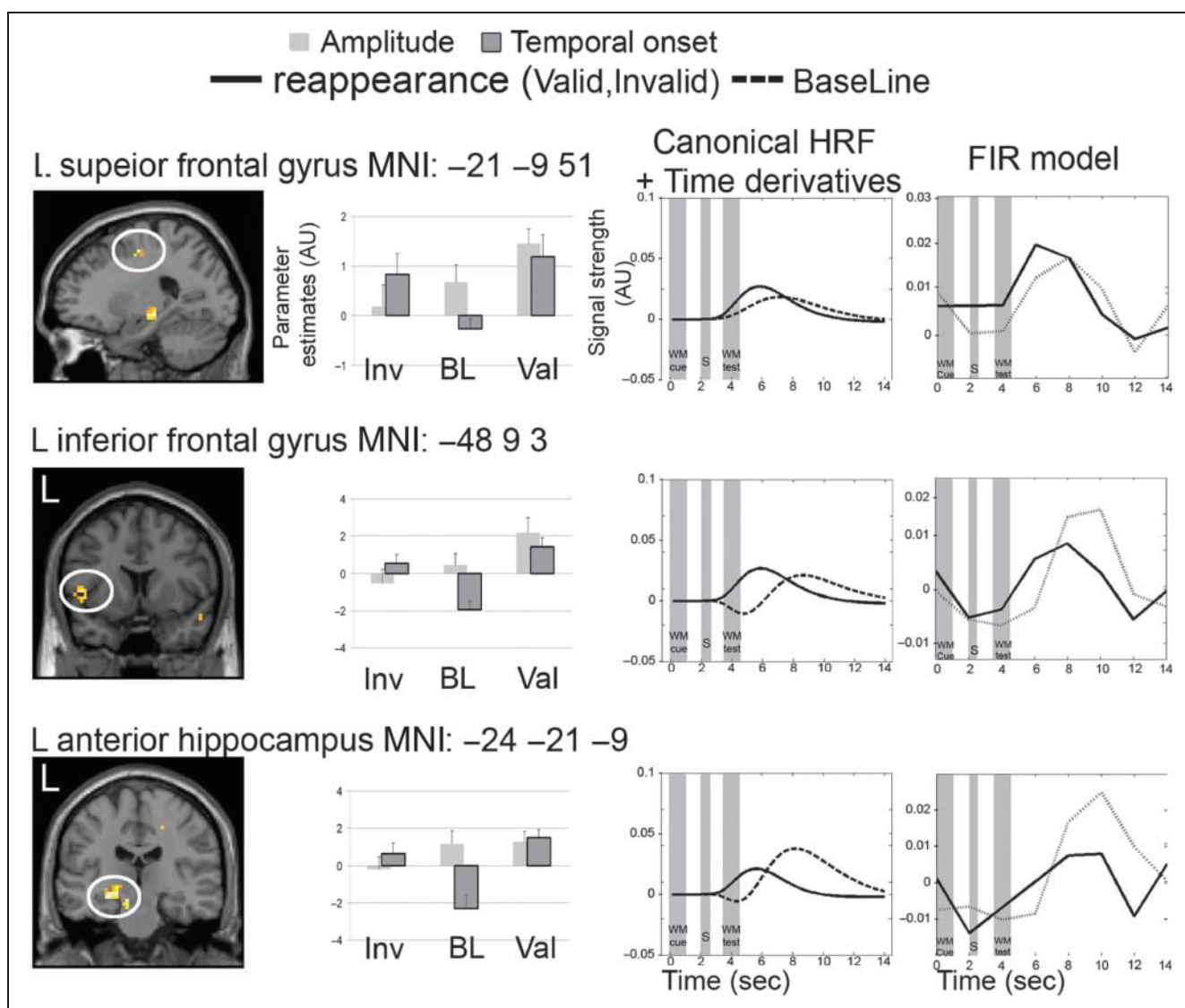


Figure 4. Interaction of the WM content and search display, effects on response onset. Reappearance of the WM cue in the search ([invalid + valid] – baseline) modulated the shape of the HRF response. These effects were tested using an F test in which the reappearance effect was tested on both the cHRF betas and their TDerv betas (see Methods). For presentation purposes, effects are presented at $p < .005$, uncorrected and overlaid on the T1 canonical template of SPM5. The graphs represent various parameters relating to the response of each region as noted above each row. The bar plots (second column) represent the size of the betas, light gray represents the cHRF, and dark gray represents the TDerv. The blacked-out line of the bars emphasizes the betas that were most informative to that contrast, in this comparison the betas of the TDerv. The third column represents the time course of the estimated HRF response for each condition ($[\beta_1 \times \text{cHRF} + \beta_2 \times \text{TDerv}]$, see Methods). The fourth column represents the responses of these regions as estimated using FIR base function, which do not presume any specific cHRF shape (see Methods).

guidance effects appear to depend on the appropriate load conditions being present. Nevertheless, we did find evidence for an effect of the WM item on memory performance, with memory performance reducing when the cue was invalid. We attribute this to participants inhibiting the distractor face, when it was incorrectly selected. Note that the inhibitory effect on memory performance also goes against the idea that participants deliberately attended to stimuli in the search display that matched the item in WM to refresh the information in WM. Here selecting the distractor was associated with worse rather than better (refreshing) memory. In addition, our evidence indicates that the interaction between WM and search is based on

information abstracted from the original modalities of input (written words for the WM stimulus, faces for the search display). This is consistent with matches operating through an episodic buffer (Baddeley & Hitch, 2000), where the semantic content of stimuli may be represented.

The neural interaction between WM and sensory processing was revealed here by differences in onset and peak time only (and there were no differences in amplitude). The reappearance of an expression in the search display that matched the emotionality of the WM word (valid + invalid) elicited an earlier onset and peak responses compared with trials where none of the expressions matched the WM. This effect was observed in

Table 3. *F* Test Reappearance Effect on Shape of HRF: cHRF (Valid + Invalid vs. Baseline) and TDerv (Valid + Invalid vs. Baseline)

Anatomy	BA	<i>F</i> (2,54)	<i>Z</i>	<i>MNI</i> (<i>x</i> , <i>y</i> , <i>z</i>)
<i>Frontal</i>				
IFG ^a	48	8.80	3.29	-48 9 3
SFG ^a	6	9.84	3.51	-21 -9 51
mOFC ^a	11	11.30	3.78	21 36 -6
lOFC ^a	11	10.14	3.53	-27 45 -12
<i>Subcortical</i>				
aHipp		11.19	3.76	-24 -21 -9
SN ^a		9.18	3.37	-9 -21 -15

aHipp = anterior hippocampus; SFG = superior frontal gyrus; LOS = lateral occipital sulcus; pSTS = posterior occipital sulcus; IFG = inferior frontal gyrus; SN = substantia nigra; aSTS = anterior superior temporal sulcus; CG = cingulate gyrus; LOS = lateral occipital sulcus; OFG = orbital frontal gyrus.

^aCluster smaller than 30 mm³.

anterior hippocampus and superior and inferior frontal gyri. The notion that processing efficiency of faces may be reflected by response onset and peak time has been proposed before (Henson, Price, Rugg, Turner, & Friston, 2002) based on evidence that repetition of faces can “speed” response time compared with novel stimuli. This earlier response may also indicate short-term facilitation of synaptic strength in these regions that has been associated with WM processing (Fujisawa, Amarasingham, Harrison, & Buzsaki, 2008). One difference between the present imaging data and those of Soto et al. (2007) is that, in their study, reappearance of identical memory items affected the amplitude of neural activity. In particular, an active memory trace (WM) of an item increased responses. These effects were reported in the lingual, superior frontal, and parahippocampal gyri (Soto et al., 2007). Note that the above regions are close to the areas observed in the current study: anterior hippocampus and superior frontal gyrus. This suggests that, in both studies, the interactions between WM and sensory processing were reflected in the responses of these regions, but in a different way. The apparent discrepancy may reflect the fact that Soto et al. found stronger behavioral effects of WM content on search compared with the current study. Several potential explanations can be put forward to account for this. One reason is that we manipulated semantic similarity here, whereas Soto et al. used visual WM cues as well as visual search displays. Effects of attentional guidance from WM may be stronger if there are matches from visual as well as more abstract WM representations. Against this, it might be argued that Soto and Humphreys (2007) have found equivalent memory guidance from words and visual shapes. However, they used words referring to specific

shapes and colors. Here we used an abstract emotional descriptor not referring to the specific form of the emotional expression present in the search display (e.g., the general term “happy” rather than a descriptor of a particular happy face). The more abstract descriptor here could weaken guidance from verbal WM. In addition, as we have noted, gender discrimination may have been accomplished in parallel, without selecting the target. In contrast, the search task in Soto et al. required discrimination of a target orientation within a shape, which may have required selection of the target stimulus, while the task involved only the detection of a target. One other explanation relates to the delay between the WM cue and the search display (here 1 sec; in the previous study, less than 0.5 sec; Soto et al., 2007, 2008; Soto & Humphreys, 2007). It is possible that longer delays enabled relatively slow executive control functions to influence search, making search more affected by the task goals rather than the unrelated contents of WM (Han & Kim, 2009). Whichever the case, we suggest that amplitude effects may be directly linked to the strength of attention capture. In the absence of amplitude changes to a reappearance of the WM content, there can be only weak deployment of attention to items matching the WM content.

In line with the above interpretation, neural activity across most regions that responded during the experimental conditions was larger on valid trials than on invalid trials. This pattern of response reflects the interaction between the WM and the task goal of visual selection, as exerted by the executive control functions. In accordance with previous studies, the strongest manifestation of this interaction was in the pulvinar and superior frontal polar (BA 10; Soto et al., 2007). We also showed strong foci of interaction in the lateral orbital frontal cortex and the lateral occipital sulcus. These last findings are in line with previous reports that use delayed match-to-sample tasks using facial expressions (LoPresti et al., 2008). Our current findings extend this prior work by demonstrating that these areas are sensitive to the attention signals based on the relevance of WM stimuli for visual selection.

It is interesting that the fronto-pulvinar network showed a similar pattern of responses to that found by Soto et al. (2007), despite the different stimuli used both for the WM and the selection task. In the current study, the WM task was to remember an emotional word, whereas in the study of Soto et al., the task was to remember a simple geometrical shape; in our study, observers searched for a specific gender among faces, whereas in the study of Soto et al., the task was to search for a tilted line and indicate to its orientation. This suggests a general role for the fronto-pulvinar network in monitoring and in setting attention priorities based on the relevance of the content of WM for search goals and vice versa. We also extended the work of Soto et al. by showing that most regions involved in the two tasks showed a similar response bias, with a larger response to the valid compared with the invalid trials. Intriguingly, this was observed at apparently

early stages of visual processing (posterior occipital cortex) and at later stages of processing related to response output (central sulcus). It is therefore tempting to speculate that signals from the front-pulvinar network are projected through different brain areas modulating several stages of processing: from early sensory processing up to selection and production of a response.

Unlike Soto et al. (2007), we did not include a baseline condition here in which participants had to classify the initial cue but did not hold it in memory. Because we used a verbal cue and a visual search target, there should be minimal guidance of attention from low-level matches between the physical properties of the stimuli here. Nevertheless, it could be argued that automatic activation of the emotion, from the verbal descriptor, influenced performance even if the descriptor was not held in WM. One case against this is that, in Soto et al., the baseline condition led to an opposite pattern of activity compared with the WM condition, with neural activity decreasing when the cue reappeared in the search display. This suggests that passive priming is associated with a neural adaptation effect, which is overridden when there is a match between the search display and a stimulus in WM. We found no evidence for adaptation in the present study. In addition, Soto et al., observed cue validity effects only for the WM condition and not for the mere repetition condition. Thus, overall, the pattern of activation reported here more closely resemble the WM effects reported by Soto et al., although we cannot conclusively rule out the possibility that affective priming processes were involved.

In conclusion, we showed that interactions between WM and visual selection processes can occur at a semantic level and can reflect the overlap in the emotional content of stimuli. Two types of neural marker were observed. WM can influence sensory processing by affecting the onset and the peak time of responses in left anterior hippocampus and prefrontal cortex. In addition, WM can affect visual selection via a fronto-pulvinar network linking bilateral orbital frontal cortex and lateral occipital sulcus. The current findings bolster the conclusion that WM can modulate both visual sensory processing and selective attention to search displays.

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REFERENCES

- Andersson, J. L., Hutton, C., Ashburner, J., Turner, R., & Friston, K. J. (2001). Modeling geometric deformations in EPI time series. *Neuroimage*, *13*, 903–919.
- Ashburner, J., & Friston, K. J. (2003a). Rigid body transformation. In R. S. Frackowiak, K. J. Friston, C. Frith, R. J. Dolan, C. Price, S. Zeki, et al. (Eds.), *Human brain function* (2nd ed., pp. 635–654). Oxford, UK: Academic Press.
- Ashburner, J., & Friston, K. J. (2003b). Spatial normalization using basis functions. In R. S. Frackowiak, K. J. Friston, C. Frith, R. J. Dolan, C. Price, S. Zeki, et al. (Eds.), *Human brain function* (2nd ed., pp. 655–672). Oxford, UK: Academic Press.
- Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*, *5*, 119–126.
- Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 780–790.
- Baddeley, A. D. (1993). Verbal and visual subsystems of working memory. *Current Biology*, *3*, 563–565.
- Baddeley, A. D., & Hitch, G. J. (2000). Development of working memory: Should the Pascual-Leone and the Baddeley and Hitch models be merged? *Journal of Experimental Child Psychology*, *77*, 128–137.
- Belke, E., Humphreys, G. W., Watson, D. G., Meyer, A. S., & Telling, A. L. (2008). Top-down effects of semantic knowledge in visual search are modulated by cognitive but not perceptual load. *Perception and Psychophysics*, *70*, 1444–1458.
- Chanon, V. W., & Hopfinger, J. B. (2008). Memory's grip on attention: The influence of item memory on the allocation of attention. *Visual Cognition*, *16*, 325–340.
- Chelazzi, L., Miller, E. K., Duncan, J., & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature*, *363*, 345–347.
- Courtney, S. M., Petit, L., Maisog, J. M., Ungerleider, L. G., & Haxby, J. V. (1998). An area specialized for spatial working memory in human frontal cortex. *Science*, *279*, 1347–1351.
- Deichmann, R., Gottfried, J. A., Hutton, C., & Turner, R. (2003). Optimized EPI for fMRI studies of the orbitofrontal cortex. *Neuroimage*, *19*, 430–441.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222.
- Downing, P. E. (2000). Interactions between visual working memory and selective attention. *Psychological Science*, *11*, 467–473.
- Friston, K. J., Fletcher, P., Josephs, O., Holmes, A., Rugg, M., & Turner, R. (1998). Event-related fMRI: Characterizing differential responses. *Neuroimage*, *7*, 30–40.
- Friston, K. J., Glaser, D. E., Mechelli, A., Turner, R., & Price, C. (2003). Hemodynamic modeling. In R. S. Frackowiak, K. J. Friston, C. Frith, R. J. Dolan, C. Price, S. Zeki, et al. (Eds.), *Human brain function* (pp. 823–842). Oxford, UK: Academic Press.
- Fujisawa, S., Amarasingham, A., Harrison, M. T., & Buzsaki, G. (2008). Behavior-dependent short-term assembly dynamics in the medial prefrontal cortex. *Nature Neuroscience*, *11*, 823–833.
- Han, S. W., & Kim, M. S. (2009). Do the contents of working memory capture attention? Yes, but it's under control. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 1292–1302.
- Henson, R. N., Price, C. J., Rugg, M. D., Turner, R., & Friston, K. J. (2002). Detecting latency differences in event-related BOLD responses: Application to words versus nonwords and initial versus repeated face presentations. *Neuroimage*, *15*, 83–97.

- Huang, L., & Pashler, H. (2007). Working memory and the guidance of visual attention: Consonance-driven orienting. *Psychonomic Bulletin & Review*, *14*, 148–153.
- Kiebel, S., & Holmes, A. (2003). The general linear model. In R. S. Frackowiak, K. J. Friston, C. Frith, R. J. Dolan, C. Price, S. Zeki, et al. (Eds.), *Human brain function* (2nd ed., pp. 725–760). Oxford, UK: Academic Press.
- LoPresti, M. L., Schon, K., Tricarico, M. D., Swisher, J. D., Celone, K. A., & Stern, C. E. (2008). Working memory for social cues recruits orbitofrontal cortex and amygdala: A functional magnetic resonance imaging study of delayed matching to sample for emotional expressions. *Journal of Neuroscience*, *28*, 3718–3728.
- Moore, E., Laiti, L., & Chelazzi, L. (2003). Associative knowledge controls deployment of visual selective attention. *Nature Neuroscience*, *6*, 182–189.
- Olivers, C. N. (2008). Interactions between visual working memory and visual attention. *Frontiers in Bioscience*, *13*, 1182–1191.
- Olivers, C. N., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 1243–1265.
- Paivio, A., & te Linde, J. (1980). Symbolic comparisons of objects on color attributes. *Journal of Experimental Psychology: Human Perception and Performance*, *6*, 652–661.
- Penny, W., Holmes, A., & Friston, K. J. (2003). Random effects analysis. In R. S. Frackowiak, K. J. Friston, C. Frith, R. Dolan, C. Price, S. Zeki, et al. (Eds.), *Human brain function* (2nd ed., pp. 843–850). Oxford, UK: Academic Press.
- Postle, B. R., Awh, E., Jonides, J., Smith, E. E., & D'Esposito, M. (2004). The where and how of attention-based rehearsal in spatial working memory. *Brain Research, Cognitive Brain Research*, *20*, 194–205.
- Soto, D., Heinke, D., Humphreys, G. W., & Blanco, M. J. (2005). Early, involuntary top-down guidance of attention from working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 248–261.
- Soto, D., Hodsoll, J., Rotshtein, P., & Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends in Cognitive Science*, *12*, 342–348.
- Soto, D., & Humphreys, G. W. (2007). Automatic guidance of visual attention from verbal working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 730–737.
- Soto, D., Humphreys, G. W., & Heinke, D. (2006). Working memory can guide pop-out search. *Vision Research*, *46*, 1010–1018.
- Soto, D., Humphreys, G. W., & Rotshtein, P. (2007). Dissociating the neural mechanisms of memory-based guidance of visual selection. *Proceedings of the National Academy of Sciences, U.S.A.*, *104*, 17186–17191.
- Thompson, V. A., & Paivio, A. (1994). Memory for pictures and sounds: Independence of auditory and visual codes. *Canadian Journal of Experimental Psychology*, *48*, 380–398.
- Tottenham, N., Tanaka, J., Leon, A. C., McCarry, T., Nurse, M., Hare, T. A., et al. (in press). The NimStim set of facial expressions: Judgments from untrained research participants. *Psychiatry Research*.
- Townsend, J. T., & Ashby, F. G. (1983). *The stochastic modelling of elementary psychological processes*. Cambridge: Cambridge University Press.
- Worsley, K. J., & Friston, K. J. (1995). Analysis of fMRI time-series revisited—Again. *Neuroimage*, *2*, 173–181.