

## Common neural substrates for visual working memory and attention

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Humans are severely limited in their ability to memorize visual information over short periods of time. Selective attention has been implicated as a limiting factor. Here we used functional magnetic resonance imaging to test the hypothesis that this limitation is due to common neural resources shared by visual working memory (WM) and selective attention. We combined visual search and delayed discrimination of complex objects and independently modulated the demands on selective attention and WM encoding. Participants were presented with a search array and performed easy or difficult visual search in order to encode one or three complex objects into visual WM. Overlapping activation for attention-demanding visual search and WM encoding was observed in distributed posterior and frontal regions. In the right prefrontal cortex and bilateral insula blood oxygen-level-dependent activation additionally increased with increased WM load and attentional demand. Conversely, several visual, parietal and premotor areas showed overlapping activation for the two task components and were severely reduced in their WM load response under the condition with high attentional demand. Regions in the left prefrontal cortex were selectively responsive to WM load. Areas selectively responsive to high attentional demand were found within the right prefrontal and bilateral occipital cortex. These results indicate that encoding into visual WM and visual selective attention require to a high degree access to common neural resources. We propose that competition for resources shared by visual attention and WM encoding can limit processing capabilities in distributed posterior brain regions. © 2007 Elsevier Inc. All rights reserved.

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### Introduction

Visual working memory (WM) and selective attention are fundamental cognitive mechanisms, both operating at the interface between perception and action. They are related because both are concerned with the control of information, and both are postulated to have limits with respect to how much information can be processed. However, visual WM and attention have been largely studied in isolation and interactions between the two have rarely been addressed in neuroimaging studies (Awh et al., 2006).

Traditional models of human information processing characterized attention as a filtering mechanism that limits the amount of information entering a memory store (Broadbent, 1958; Atkinson and Shiffrin, 1968). In these early models, temporary memory and attention were considered distinct, associated with separate functions. There is indeed some behavioral evidence for the idea that visual WM and attention work at different stages of processing, with attention taking place earlier and controlling which sensory information gets encoded into visual WM (e.g., Duncan and Humphreys, 1989; Bundesen, 1990; Palmer, 1990; Schmidt et al., 2002). In this case, visual WM and attention might be represented by different neural substrates. However, recent models of WM suggest that selective attention and WM may rely on a common capacity-limited cognitive mechanism – “working attention” – (Baddeley, 1993). For instance, Cowan (1988) offers the view that WM is best understood as a subset of activated representations of long-term memory that is currently within the focus of attention. Selective attention has been implicated as a limiting factor for the storage capacity of visual WM (Cowan, 1998, 2001; Wheeler and Treisman, 2002). This view predicts that visual WM and attention share common neural resources.

Frontal and parietal brain regions are the primary areas involved both in WM and visual attention (Pessoa and Ungerleider, 2004). Overlap of the cerebral networks of WM and attention has been demonstrated in targeted comparisons (LaBar et al., 1999; Pollmann and von Cramon, 2000; Corbetta et al., 2002). Also,

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spatial attention to representations held in WM is subserved by fronto-parietal brain regions similar to those recruited for spatial orienting in the perceptual domain (Nobre et al., 2004; Lepsien et al., 2005). However, neuroanatomic overlap alone cannot be interpreted as direct evidence for common neural and cognitive mechanisms because a small-scale regional specialization may exist below the resolution of functional imaging (Nieder, 2004). Moreover, neurons within the same anatomical region may carry out task-specific adaptive functions (Rao et al., 1997), evoking the impression that different cognitive functions, e.g., WM and selective attention, are mediated by the same cortical region. Finally, overlap between the neural substrates that support WM and attention does not necessarily entail a functional relationship between the two cognitive domains. For example, one cannot exclude that shifts of visuospatial attention associated with activation of a given brain region are epiphenomenal to the core processes that encode and maintain information in visual WM (Awh et al., 2006). By demonstrating that memory performance declines when shifts of attention are prevented, it becomes possible to infer a true functional role of attention in visual WM (Smyth and Scholey, 1994; Awh et al., 1998; Oh and Kim, 2004; Woodman and Luck, 2004).

The conceptual link between visual WM and attention addressed in our study stems from one characteristic feature of visual WM and attention, namely their limitation in capacity. The rate at which visual information can be attended is severely limited (Duncan et al., 1994) as is the number of objects that can be simultaneously attended among distractors. Only about four moving objects can be tracked simultaneously (Pylyshyn and Storm, 1988; Culham et al., 2001; Scholl, 2001; Cavanagh and Alvarez, 2005). In a similar vein, humans are able to actively maintain only up to four objects in visual WM (Phillips, 1974; Pashler, 1988; Logie, 1995; Luck and Vogel, 1997; Cowan, 2001).

It has recently been demonstrated that the capacity limit of visual WM is reflected in the posterior parietal cortex by a load-dependent increase in blood oxygen-level-dependent (BOLD) activation that reaches a plateau when the capacity limit is approached (Linden et al., 2003; Todd and Marois, 2004; Xu and Chun, 2006). That is, a limit in cognitive processing is correlated with a limit in neural activation, namely a plateau in BOLD activity that cannot be exceeded with increasing demands. We reasoned that if visual WM and attention shared common capacity-limited cognitive and neural resources, these resources would become exhausted in conditions that make high demand on both processes, thus resulting in interference. The present experiment was therefore motivated by the need to orthogonally manipulate the demand on WM and attention within one single task and to identify brain areas which showed an interference effect.

Participants performed easy or difficult visual search in order to encode one or three complex objects into visual WM (Fig. 1A). Attentional demand was manipulated by implementing two search conditions in which target items had either unique features (i.e., color) and were highly discriminable from the distractors (“easy search” (ES)=low attentional demand) or shared the features with the distractors and were thus difficult to discriminate (“difficult search” (DS)=high attentional demand) (Treisman and Gormican, 1988; Duncan and Humphreys, 1989).

Traditionally, visual WM tasks distinguish the encoding phase, associated with the transfer of information generated from perceptual input into durable storage (Jolicoeur and Dell’Acqua, 1998), from the delay period, during which the information is

actively maintained (Courtney et al., 1997; Munk et al., 2002; Ranganath et al., 2004), and the retrieval phase, where a test item has to be compared to the stored information (Pessoa et al., 2002; Bledowski et al., 2006). Neural capacity constraints for visual WM have been observed both during the encoding and maintenance of visual information (Linden et al., 2003; Todd and Marois, 2004; Vogel and Machizawa, 2004; Xu and Chun, 2006). Here we focused on the encoding phase during which we presented the search array. Physical properties of the stimulus display were identical across conditions, which ruled out differences in brain activation owed to differences in sensory stimulation. By applying the additive factors approach, the present paradigm allowed us to differentiate between three patterns of activation that were associated with different contributions to the cognitive task components. First, an exclusive main effect for difficulty of either encoding into WM or attentional selection would be expected in areas that preferentially subserve that particular task component. Second, overlap areas that mediate both processes would show main effects for both task manipulations with an additive increase in BOLD activation as a consequence of an increase in the demands on WM encoding and visual search difficulty. Third and most importantly, we expected to reveal areas showing an interaction effect between attentional demand and WM load. Activation in these regions should demonstrate a less than additive increase in BOLD activation with increasing demands on WM and visual search. Thus, activation should reach a plateau as WM and attentional demands increase with the difference in the BOLD response between WM load 3 and WM load 1 levelling off in the difficult search condition. Such interference would indicate a limitation of the neural resources available for WM encoding and attentional processing and offer direct evidence for common neural resources shared by the processes of encoding into visual WM and visual selective attention.

## Materials and methods

### *Pilot behavioral study*

#### *Participants*

18 participants (12 females, mean age  $25.9 \pm 3.9$ , range: 19–32) were recruited from an academic environment and volunteered in this study. Participants reported normal or corrected-to-normal visual acuity, normal color vision, and no history of neurological or psychiatric illness. The study was approved by the local ethics committee. All participants gave written informed consent.

#### *Stimuli and task*

The stimuli were presented through a PC on a 17-in. color monitor using ERTS (Experimental Run-Time System, Berisoft, Frankfurt, Germany). A chinrest was used to minimize head motion and to ensure that the observer’s eyes were positioned in a constant distance of 42 cm from the screen. Response keys were located on the computer keyboard. The experiments were performed in a dimmed room.

The display in the study phase consisted of nine different grey geometric shapes (each spanning approximately  $1.1^\circ \times 1.1^\circ$  of visual angle), arranged in a  $3 \times 3$  matrix, and presented in the center of the screen and on a black background (Fig. 1A and B). The shapes were selected at random without replacement from a set of 12 shapes and each was oriented randomly in one of the four directions  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ , and  $270^\circ$ . Participants thus had to discriminate 48 different

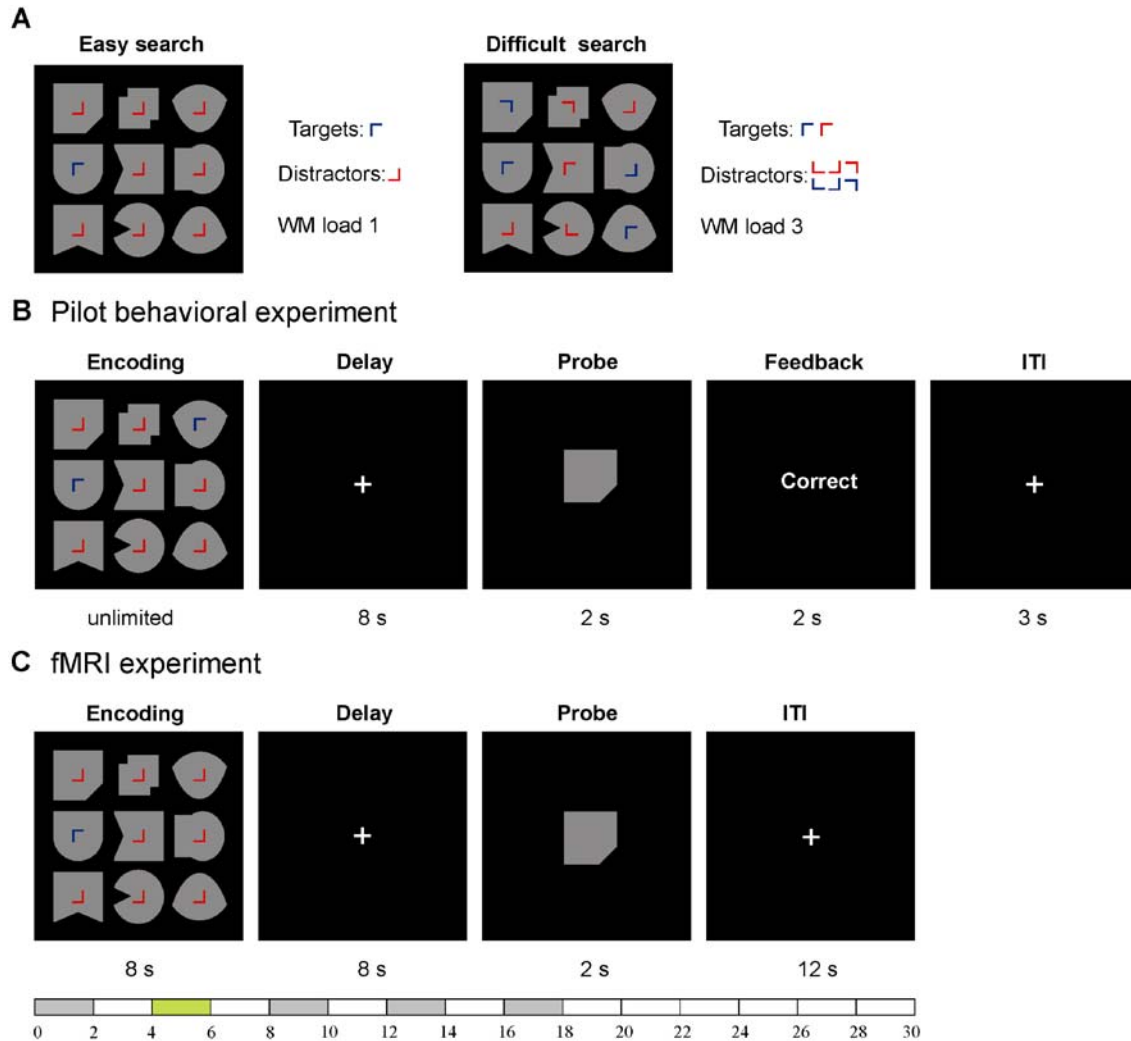


Fig. 1. Stimuli and trial design. (A) Stimuli used in the pilot behavioral study and the fMRI experiment. Participants were presented with a search array and asked to memorize only the objects marked with a target item. The targets were either easy to discriminate from the distractors (“easy search”) or not (“difficult search”). WM load was manipulated by changing the number of targets (load 1, left array; load 3, right array). (B) Trial design used in the pilot behavioral study. Each trial began with the presentation of the search array, which remained visible until the participant pressed the response key. WM load varied from 1 to 5. After a blank delay interval, participants decided whether a probe consisting of a single object matched one of the memorized objects. (C) Trial design used in the fMRI experiment. The search array was presented for 8 s and WM load was either 1 or 3. The analysis focused on the late encoding predictor (green bar, grey: additional predictors). ITI: intertrial interval.

objects. In the center of each shape we placed a small L-shaped item ( $0.3^\circ \times 0.3^\circ$ ). The L's appeared in one of four different orientations ( $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ , and  $270^\circ$ , clockwise) and were colored either blue or red. Participants needed to memorize only the shapes associated with an L oriented  $90^\circ$  (target items). The shapes associated with Ls of other orientations could be ignored (distractor items). The number of target items within each display varied randomly between one and five. In the easy search condition target L's always appeared in blue and distractors in red. Distractor L's were always oriented  $270^\circ$ . In the difficult search condition each target and distractor was assigned randomly either blue or red color. In this condition, the distractor items could take any of the remaining three orientations ( $0^\circ$ ,  $180^\circ$ , and  $270^\circ$ ). In the test phase participants were presented with a single shape in the center of the screen and without the center item. The luminance of the shapes, the blue, and the red center items was 12.3, 6.01, and  $9.87 \text{ cd/m}^2$ , respectively. The background luminance was

$0.01 \text{ cd/m}^2$ . During the delay period a white central fixation cross was presented on a blank screen ( $0.2^\circ \times 0.2^\circ$ ,  $60.06 \text{ cd/m}^2$ ).

*Design and procedure*

We used a  $2 \times 5$  within-subjects factorial design, with two levels of attentional demand (easy vs. difficult search) and five levels of WM load, determined by the number of targets (WM load 1 to WM load 5). Each of the 10 experimental conditions was presented equally often (12 trials per condition). Easy and difficult search conditions were presented in separate blocks of 10 trials, with six blocks for each condition. This amounted to a total of 120 experimental trials per participant. The trials were fully randomized within blocks and pseudo-randomized across blocks and across participants. Before starting a new block, participants were always given an instruction about the targets they needed to search for. At the beginning of the experiment participants performed two

practice blocks of 10 trials, one for each of the two attentional conditions.

Each trial began with the presentation of the nine-item array, which remained visible until the participant pressed the response key (Fig. 1B). Participants had to discriminate the target items from the distractors and to memorize the shapes associated with targets. The time they needed to achieve high memory performance, indicated by a key-press, was used as a dependent variable (presentation time). We also instructed participants to emphasize accuracy over speed in order to ensure that response accuracy was high and comparable across different attentional-demand conditions. After the display disappeared participants fixated a cross during a delay period of 8 s, which was followed by the presentation of a single test shape. Participants were then required to indicate whether the test shape matched in the form and orientation one of the target shapes presented previously by pressing the “Y” or “N” key for match and non-match, respectively. We recorded response accuracy and reaction times at test. After each response feedback was given (“Wrong”, “Correct” or “No Response”), which was followed by an inter-trial interval of 3 s. Analyses of presentation times included only correct trials.

### fMRI experiment

#### Participants

18 healthy participants (9 females, mean age  $28.2 \pm 6.6$ , range: 20–44) were recruited from an academic environment. Participants reported normal or corrected-to-normal visual acuity, normal color vision, and no history of neurological or psychiatric illness. The study was approved by the local ethics committee. All participants gave written informed consent.

#### Stimuli, task and procedure

The stimuli and task were the same as in the pilot behavioral study, except for the following differences. To provide constant visual stimulation across experimental conditions the search array was presented for the same amount of time in each trial. Thus, each 30-s trial began with the presentation of the search array for 8 s. As in the pilot behavioral study, participants needed to memorize only the objects marked with an L in  $90^\circ$  orientation (target items). The objects associated with Ls of other orientations could be ignored (distractor items). The search array contained either one or three targets (WM loads 1 and 3). After an 8-s delay interval, a probe that consisted of a single object appeared for 2 s at the center position of the array. Participants responded with a left- or right-hand button press to indicate whether the probe did or did not match in the form and orientation one of the memorized objects. Feedback was not provided. Half of the trials were matches. The inter-trial interval lasted 12 s (Fig. 1A and C). Each fMRI run (four runs per session) included six iterations of each of the four trial types (load 1/ES; load 3/ES; load 1/DS; load 3/DS). We presented easy and difficult search conditions in separate blocks of six trials (two blocks for each condition per run) in a pseudo-randomized order across runs. WM load conditions were fully randomized within each block.

#### Image acquisition and analysis

Anatomical three-dimensional T1-weighted images and functional images were acquired on a 3 T Magnetom Trio scanner (Siemens Medical Systems, Erlangen, Germany) equipped with a standard head coil. Functional images were collected using 34 slices (3 mm thickness with  $3.4 \times 3.4$  mm in-plane resolution)

covering the whole brain with a BOLD-sensitive EPI sequence (TR=2 s, TE=30 ms, FA=80°; FOV=220 mm, matrix=64×64; duration of each run=780 s).

Image analyses were performed with Brainvoyager QX, version 1.4.9 (Brain Innovation, Maastricht, The Netherlands). Data preprocessing included slice scan time correction with the first scan time within a volume used as a reference for alignment by sinc interpolation, three-dimensional motion correction, spatial smoothing with an 8 mm Gaussian kernel (full width at half-maximum), temporal high pass filtering with a cut-off of 260 s to remove low-frequency non-linear drifts of three or fewer cycles per time course, and linear trend removal. Talairach transformation was performed for the complete set of functional data of each subject, yielding a 4-D data representation (volume time course:  $3 \times \text{space}$ ,  $1 \times \text{time}$ ). A multi-subject statistical analysis was performed by multiple linear regression of the BOLD response time course in each voxel. The general linear model of the experiment was computed for 72 *z*-normalized volume time courses (18 participants×4 runs). For each of the four experimental conditions, five task phases were defined representing early encoding (0–4 s) and late encoding (4–8 s), early delay (8–12 s) and late delay (12–16 s) and retrieval (16–18 s). The different task phases were modelled by predictors of 2-s duration in order to avoid contamination by variance in the fMRI signal attributable to neural activity that occurred in the preceding or subsequent task phases (Fig. 1C) (Zarahn et al., 1997). The signal values during these phases were considered the effects of interest. The corresponding predictors were obtained by convolution of an ideal box-car response with a gamma function model of the hemodynamic response (Friston et al., 1998). All error trials were collapsed on a separate predictor.

3D group statistical maps were generated by associating each voxel with the *F*-value corresponding to the specific set of predictors and calculated on the basis of the least mean squares solution of the general linear model with a random-effects model. The obtained beta weights of each predictor served as input for the second-level whole-brain random-effects analysis including a  $2 \times 2$  factorial design. Thus, the beta values of participants were treated explicitly as realizations of the two within-subjects factors attentional demand (level 1: ES, level 2: DS) and WM load (level 1: load 1, level 2: load 3), which allowed us to directly test for an interaction between the two based on *F*-statistics. To compare activations between experimental conditions within one task phase, linear contrasts were performed using *t*-statistics. Multi-subject statistical maps were thresholded at  $q < 0.05$ , corrected for false discovery rate (Genovese et al., 2002) and visualized on a surface reconstruction of the MNI template brain (courtesy of the Montreal Neurological Institute). fMRI time courses were shown for selected regions of interest (ROI) where the effects of WM load and attentional demand appeared most prominently. ROIs were functionally defined based on the multi-subject statistical maps overlaid on the cortical surface map of the MNI template brain. Starting from the voxel showing peak activation in the multi-subject map, a surface patch of  $30 \text{ mm}^2$  (4 mm thickness) was marked. Representative time courses for each experimental condition were obtained by averaging the percent signal changes of the individual voxels within the obtained volume across all participants and repetitions.

An additional analysis was performed in order to quantify differences in the latency of the peak activation between easy and difficult search conditions during WM encoding in selected ROIs. For each experimental condition, we extracted the time-of-peak point from each individual time course within a time window of



two to eight volumes after stimulus onset. In those cases where there was more than one peak during the defined time window we always used the first peak to define the time-of-peak point. As this procedure was applied evenly across conditions, it should not have biased the resulting latency differences. Latency differences between easy and difficult search conditions were then compared using *t*-statistics.

To assess the influence of differential search speed in the easy and difficult search conditions on the interaction between search difficulty and WM load, we divided the encoding phase (0–8 s) into four phases of 2-s duration each (E1: 0–2 s, E2: 2–4 s, E3: 4–6 s, E4: 6–8 s). Each encoding phase was modelled separately by predictors of 2-s duration that were obtained by shifting an ideal box-car response (assuming a value of 1 for the volumes of the respective encoding phase and a value of 0 for the remaining time points) by 4 s to account for the hemodynamic delay. Linear contrasts representing 3-way interactions between the factors search difficulty (ES vs. DS), WM load (3 vs. 1) and encoding phase (E1 vs. E2; E1 vs. E3; E1 vs. E4; E2 vs. E3; E2 vs. E4; E3 vs. E4) were calculated separately to test whether search speed had an effect on the interaction between search difficulty and WM load.

**Results**

*Pilot behavioral study*

A repeated-measures analysis of variance (ANOVA) tested the effects of search difficulty (ES vs. DS) and WM load (loads 1 to 5) on response accuracy and reaction time (RT) at test and the individual presentation time of the search array. Response accuracy to the probe object and RTs did not differ between the two search conditions [84% correct across WM loads for ES and DS, ANOVA,  $F(1,17)=0.26$ ,  $p=0.62$ ; 986 ms and 992 ms for ES and DS, respectively, ANOVA,  $F(1,17)=0.21$ ,  $p=0.66$ ]. A strong main effect was observed only for WM load. Response accuracy declined from WM load 1 to WM load 5 [from 90% correct with WM load 1 to 73% correct with WM load 5, for ES; from 92% correct with WM load 1 to 80% correct with WM load 5, for DS; ANOVA,  $F(4,68)=16.24$ ,  $p<0.001$ ], whereas RTs significantly increased [from 781 ms with WM load 1 to 1098 ms with WM load 5, for ES; from 841 ms with WM load 1 to 1053 ms with WM load 5, for DS; ANOVA,  $F(4,68)=43.05$ ,  $p<0.001$ ]. The interaction between the two factors was significant only for RTs [ $F(4,68)=3.58$ ,  $p<0.05$ ]. As the WM performance at test was the same across the two search conditions, we then analyzed the time needed for successful encoding into WM.

The encoding time, as measured in terms of the duration of the search array required by individual participants, increased as a function of WM load [ANOVA,  $F(4,68)=48.09$ ,  $p<0.001$ ] and as a function of search difficulty [ $F(1,17)=130.94$ ,  $p<0.001$ ]. The interaction WM load × search difficulty was not significant [ $F(4,68)=0.98$ ,  $p=0.41$ ]. Thus, the presentation times were consistently longer with difficult than with easy search across all five WM load conditions and always by the same amount of about 4 s (Fig. 2A). With regard to the experimental conditions implemented in the fMRI experiment (load 1/ES, load 3/ES, load 1/DS, load 3/DS) the mean presentation times ranged from 1.8 s in the easiest condition (load 1/ES) to 10.2 s in the most difficult search condition (load 3/DS). We considered that overall times were probably slightly longer than actually needed for encoding owing to the instruction to emphasize accuracy over speed and the self-

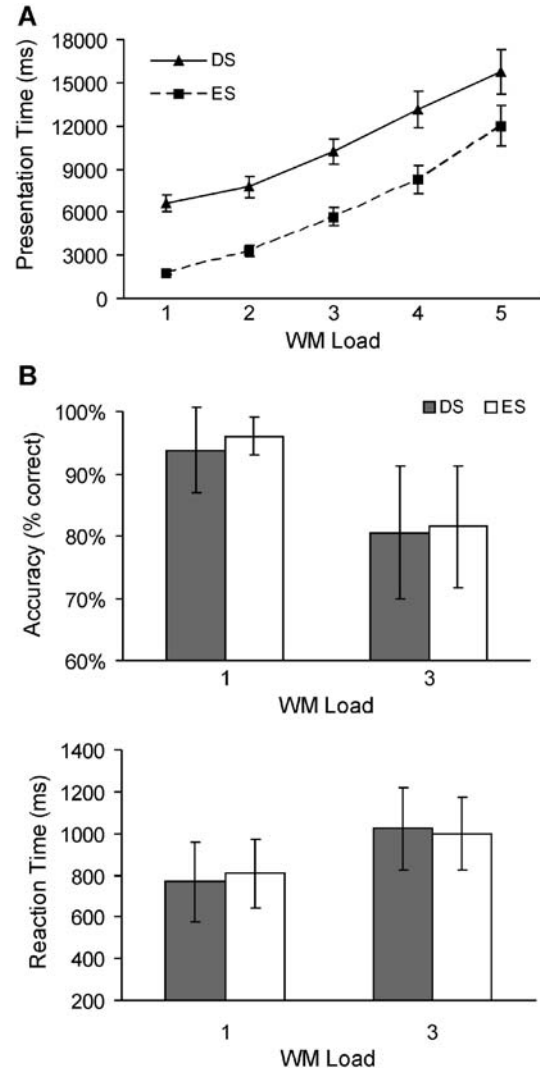


Fig. 2. Behavioral results. (A) Pilot behavioral study. Presentation times needed to achieve high memory performance for five different levels of WM load. (B) fMRI experiment. Mean response accuracy and reaction times in the four experimental conditions. Bars represent standard errors of the mean. ES: easy search, DS: difficult search.

paced procedure and therefore selected an encoding phase of 8 s for the fMRI experiment. We reasoned that this time would be long enough to enable successful encoding of the objects into WM, both in the easy and in the difficult search conditions. Assuming that visual search difficulty would not have an impact on processing after the array had disappeared (during maintenance and retrieval of the WM task) we therefore expected that performance at test would not differ between easy and difficult search conditions in the fMRI experiment.

*fMRI experiment*

*Behavioral performance*

An ANOVA tested the effects of search difficulty (ES vs. DS) and WM load (load 1 vs. load 3) on response accuracy and RT at test. Participants' WM performance at test was equally good under easy and difficult search [WM load 1, 96.1% and 93.8% correct,

respectively; WM load 3, 81.5% and 80.6% correct; ANOVA,  $F(1,17)=2.68$ ,  $p=0.12$ ]. RTs to the probe object did not differ between the easy and difficult search conditions either [WM load 1, 807 ms and 769 ms, respectively; WM load 3, 998 ms and 1022 ms;  $F(1,17)=0.27$ ,  $p=0.61$ ] (Fig. 2B). A strong main effect was observed only for WM load. In both search conditions response accuracy declined from WM load 1 to WM load 3 [on average by 13.9 percentage points,  $F(1,17)=70.37$ ,  $p<0.001$ ], and RTs were significantly slower on average by 222 ms [ $F(1,17)=202.14$ ,  $p<0.001$ ]. The interaction between search difficulty and WM load reached significance only for RTs [ $F(1,17)=6.88$ ,  $p<0.05$ ]. The finding that memory performance at test did not differ between easy and difficult search conditions indicates that the presentation time of the search array (8 s) was indeed sufficiently long to ensure that participants were able to complete the encoding process even in the most demanding condition (load 3/DS). Therefore, the task was suitable for probing common and selective activations for visual search and WM encoding with event-related fMRI.

#### Brain systems for attention and WM encoding

fMRI analysis focused on the late encoding phase (4–8 s) because the pilot behavioral experiment indicated that encoding times increased by about 4 s when the search changed from easy to difficult (Fig. 2A). Therefore, effects of attentional demand were expected during the later part of the stimulus presentation phase. The contrast analyses of fMRI data for the late encoding predictor (4–6 s after stimulus onset) revealed a high degree of overlap in the brain areas that showed higher activation for difficult compared to easy search [(load 3/DS+load 1/DS)–(load 3/ES+load 1/ES)] and higher activation for WM load 3 compared to WM load 1 [(load 3/ES+load 3/DS)–(load 1/ES+load 1/DS)]. Overlap in activation was observed in the occipito-temporal cortex, the lateral and medial parietal cortex (intraparietal sulcus, precuneus), along the precentral sulcus (PrcS), in the frontal midline, the insula, and the thalamus (Table 1 and Fig. 3). The fronto-parietal activation patterns were similar to those reported previously in studies that compared activation induced by attention and WM tasks (LaBar et al., 1999; Pollmann and von Cramon, 2000; Corbetta et al., 2002). In the present study, the common pattern of brain regions involved during both visual search and WM encoding also included the prefrontal cortex (PFC), with overlapping activations restricted to a part of the right middle and inferior frontal gyrus (MFG and IFG). The left MFG and IFG were selectively responsive to WM load as were regions in the left anterior inferior parietal lobule and bilateral inferior temporal cortex. In contrast, areas selectively responsive to high attentional demand were found within the right PFC (MFG and IFG) and occipital cortex. A supplementary analysis (see Supplementary material) indicated that this pattern of prefrontal activation might reflect a hemispheric specialization with left PFC selectively responsive to WM load and right PFC selectively responsive to attentional demand.

Behavioral evidence from our pilot study indicated that the two search conditions differed in the degree of search efficiency as reflected by slower processing in the difficult compared to the easy search condition. Specifically, the process of encoding was delayed by about 4 s (Fig. 2A). We conducted a supplementary analysis to examine whether the differences in activation for difficult vs. easy search during the late encoding phase were mainly driven by the varying duration of the search process (fast search with ES vs. slow search with DS). To this end we calculated the contrast between

difficult search during late encoding (4–6 s after stimulus onset) and easy search during early encoding (0–2 s after stimulus onset) [(DS/load 3/late encoding+DS/load 1/late encoding)–(ES/load 3/early encoding+ES/load 1/early encoding)]. The results were similar to those obtained for the effect of attentional demand during late encoding, albeit less widespread (see Fig. S1 and Supplementary analysis 2). Overlapping activation for the two contrasts appeared in several lateral frontal, parietal and occipital regions. Therefore, at least for these regions, the effect of attentional demand during late encoding was not likely to be overemphasized because of fast search in the ES condition.

#### Interference between attention and WM encoding

Brain areas reflecting functional interference between attention-demanding visual search and WM encoding were identified by the interaction contrast [(load 3/ES–load 1/ES)–(load 3/DS–load 1/DS)]. Significant activation was found only in a subset of the regions with overlapping activations for the attention and WM load contrasts. These regions included the occipito-temporal and posterior parietal cortex as well as the medial frontal cortex and the PrcS of both hemispheres (Table 1 and Fig. 3, dark green color). Time course analyses of these regions showed a smaller increase in BOLD signal with increasing WM load for difficult compared to easy search (Fig. 4A, purple circles). This type of interaction was most pronounced in early and higher visual areas (middle occipital gyrus, cuneus) and in the left dorsal PrcS. Here, the BOLD response was always the lowest in the easy search condition when participants needed to memorize only one object, but increased to the same degree in the remaining three conditions (Fig. 4A, red circles). Thus, in these brain areas, the BOLD response could not exceed the plateau of activation that was reached already with load 3/ES or with load 1/DS in order to respond to joint demands on WM and attention. In contrast, in adjacent brain regions that showed an overlap in activation but no interaction, the BOLD signal further increased in the most difficult condition (load 3/DS) (Fig. 4B, black circles).

Areas preferentially sensitive to WM load (but not to attentional demand) also emerged in the analysis of 2-way interactions. These included the left MFG, IFG and anterior inferior parietal lobule and the inferior temporal cortex, bilaterally (Table 1). Here, the time course of BOLD activation peaked later under conditions of difficult vs. easy visual search (Fig. 4A, orange circle) with significant differences in the latency of the peak amplitudes in the left MFG ( $t=2.8$ ,  $p<0.01$  for load 1;  $t=2.7$ ,  $p<0.01$  for load 3), the left inferior temporal cortex ( $t=4.02$ ,  $p<0.001$  for load 1;  $t=3.1$ ,  $p<0.01$  for load 3) and the left anterior IPL ( $t=4.5$ ,  $p<0.01$  for load 1;  $t=1.8$ ,  $p=0.08$  for load 3). Consistently with the delay in encoding times revealed in the pilot behavioral study (Fig. 2A), the time shift in the maximum amplitude of BOLD activation was about 4 s and appeared without any compromise on the size of the WM load effect in the difficult search condition.

The smaller effect of WM load under high attentional demand in posterior areas and the PrcS might also be driven by temporal differences between the two search conditions (slow vs. fast search). In subsequent whole-brain analyses we therefore assessed the influence of search speed on the interaction between search difficulty and WM load by calculating the interactions between the factors search difficulty, WM load and encoding phase (see Materials and methods). Significant activation reflecting a 3-way interaction was found only between the factors search difficulty (DS vs. ES), WM load (load 3 vs. load 1), and encoding phase (E3

Table 1  
Brain regions showing significant activation in the contrasts for encoding

Brain region	BA	x	y	z	Contrast			
					WM load	Attentional demand	2-way interaction	3-way interaction
<i>Common activation</i>								
R MFG	9	44	8	38	*	*		
R MFG	46	45	32	27	*	*		
R MFG	46	39	29	18	*	*		
R IFG	9/44	53	9	26	*	*		
L dlPrcS	6	-21	-12	53	*	*	*	
R dlPrcS	6	29	-7	58	*	*		
L FEF	6	-42	-10	48	*	*	*	
R FEF	6	40	-5	55	*	*	*	
L vlPrcS	6	-45	-4	41	*	*	*	*
R vlPrcS	6	47	5	38	*	*	*	
L pre-SMA	6	-5	5	53	*	*	*	*
R pre-SMA	6	4	7	55	*	*	*	*
R insula	13	32	15	13	*	*		
L insula	13	-29	23	7	*	*		
L SPL	7	-19	-65	56	*	*	*	
R SPL	7	28	-64	48	*	*	*	
L IPL	40	-38	-41	40	*	*	*	
R IPL	40	34	-54	40	*	*	*	
L precuneus	7	-16	-66	51	*	*	*	
L precuneus	7	-20	-72	35	*	*	*	*
R precuneus	7	25	-66	33	*	*	*	*
L cuneus	18	-24	-89	4	*	*	*	
R cuneus	18	26	-87	0	*	*	*	
L MOG	19	-40	-74	-10	*	*	*	
L FG	37	-40	-58	-7	*	*	*	
R FG	37	40	-59	-11	*	*	*	*
L MOG	19	-24	-80	17	*	*	*	*
R MOG	19	34	-80	17	*	*	*	*
L cuneus	19	-21	-81	32	*	*	*	*
R IOG	19	37	-75	0	*	*	*	*
R lingual gyrus	18	10	-83	-3	*	*	*	*
L thalamus		-8	-24	1	*	*		
R thalamus		7	-21	3	*	*		
<i>WM-selective</i>								
L MFG	46	-40	32	24	*		*	
L MFG/IFS	9	-47	21	28	*		*	*
L IFG	45	-52	19	7	*		*	
L IPL	40	-51	-37	40	*		*	
L ITG	19	-48	-61	-2	*		*	*
R ITG	37	53	-45	-14	*		*	
L FG	37	-44	-49	-12	*		*	
R FG	37	51	-46	-15	*		*	
L MTG	37	-50	-47	-8	*			
R MTG	37	49	-49	-1	*			
<i>Attention-selective</i>								
R MFG	9	41	23	28		*		
R IFG	46	37	32	13		*		
L PHG	19	-21	-48	-4		*		
R PHG	19	19	-46	4		*		
L lingual gyrus	19	-15	-54	0		*		
R lingual gyrus	19	13	-58	3		*		
R cuneus	31	17	-70	8		*		

Significant contrasts (whole brain random-effects analysis) for the late encoding predictor (4–6 s): (\*) indicates  $q(\text{FDR}) < 0.05$ . Talairach coordinates [x, y, z (in mm)] of the activation maxima are shown.

BA: Brodmann area, WM load: load 3 vs. load 1 ( $t=2.68$ ), Attentional demand: DS vs. ES ( $t=2.71$ ), 2-way interaction: load 3 vs. load 1  $\times$  DS vs. ES ( $F=11.28$ ), 3-way interaction: load 3 vs. load 1  $\times$  DS vs. ES  $\times$  E1 vs. E3 ( $t=4.19$ ), dlPrcS: dorsolateral precentral sulcus; FEF: frontal eye field; FG: fusiform gyrus; IFG: inferior frontal gyrus; IFS: inferior frontal sulcus; IOG: inferior occipital gyrus; IPL: inferior parietal lobule; ITG: inferior temporal gyrus; MFG: middle frontal gyrus; MOG: middle occipital gyrus; MTG: middle temporal gyrus; PHG: parahippocampal gyrus; pre-SMA: pre-supplementary motor area; SPL: superior parietal lobule, vlPrcS: ventrolateral precentral sulcus, E1: encoding phase 1 (0–2 s), E3: encoding phase 3 (4–6 s).

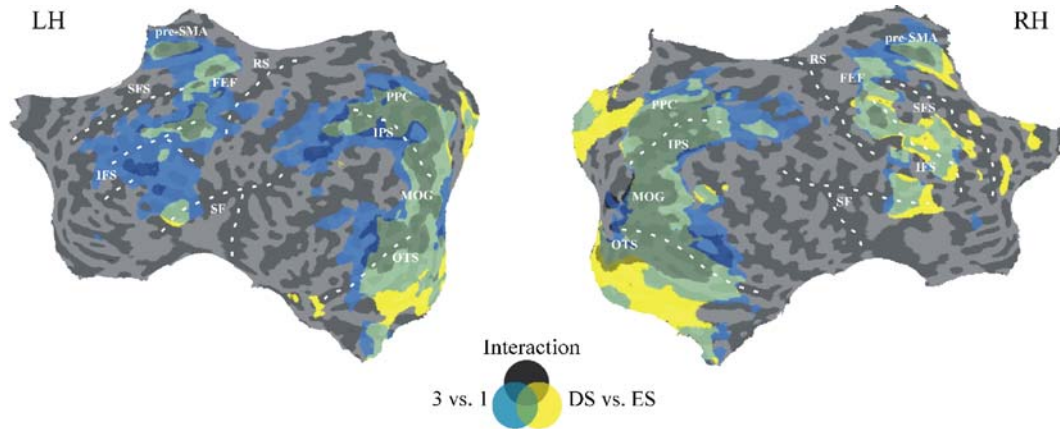


Fig. 3. Group results for the late encoding predictor (4–6 s). Statistical maps of the contrasts DS vs. ES (yellow), WM load 3 vs. 1 (blue), and the significant 2-way interaction of search difficulty  $\times$  WM load (black) are projected on the flattened surface reconstruction of the MNI template brain (courtesy of the Montreal Neurological Institute) (LH: left hemisphere, RH: right hemisphere). Activations are those exceeding a whole-brain false discovery rate threshold of  $q(\text{FDR}) < 0.05$ . FEF: frontal eye field, IFS: inferior frontal sulcus, IPS: inferior parietal sulcus, MOG: middle occipital gyrus, OTS: occipito-temporal sulcus, PPC: posterior parietal cortex, pre-SMA: pre-supplementary motor area, RS: rolandic sulcus, SF: Sylvian fissure, SFS: superior frontal sulcus.

vs. E1) bilaterally in a distributed network of occipital, temporal, and parietal areas [ $q(\text{FDR}) < 0.05$ ]. Frontal activations included the medial frontal cortex, the left ventral PrcS, and the left MFG/IFG (Table 1 and Fig. 5), the same regions where the latency of the peak amplitude between easy and difficult search had appeared most strongly (Fig. 4A). These results, again, indicated a time shift in activation produced by the difficult search. However, the observed regions differed from the areas that showed strong plateau effects during late encoding (left dorsal PrcS and bilateral visual cortex). The regions in the lateral parietal cortex that were associated with the 2-way interaction contrast did not emerge in this 3-way interaction contrast either. Thus, the decreased WM load effect under high attentional demand observed in these areas could not be explained by time shifts in peak activation between the two search conditions.

#### Load effects during WM maintenance

One goal of this study was to investigate neurophysiological interactions between attentional processes involved in visual search and the encoding of information into visual WM. We reasoned that if participants successfully performed the WM task despite the concurrent demands on attentional resources, the observed effect of interference between search difficulty and WM load should be restricted to the encoding phase. Interference between the two processes should not be observed during the subsequent delay phase. Consistent with this hypothesis, no significant activation was found for the interaction contrast between search difficulty and WM load for the late delay predictor (12–14 s after stimulus onset). Neither did the difficult vs. easy search contrast yield significant activation. Thus, the process of active maintenance of objects in WM was not limited by attentional processing required by difficult visual search. The increase in the number of objects maintained in WM (load 1 vs. load 3) was associated with significant activation mainly around the intraparietal sulcus, extending into both superior and inferior parietal lobules, the lateral prefrontal, medial frontal and premotor cortex, the temporal cortex and the insula. These activation foci were almost identical to those observed during the encoding phase, which revealed additional activation in early and higher visual areas (Fig. 6 and Table S2).

#### Discussion

In the present study we combined visual search and delayed discrimination of complex objects within one single task and independently modulated the demands on selective attention and WM encoding. The goal was to identify the brain regions that were selectively responsive to either WM or attentional demand and those involved in both processes. We hypothesized that if visual WM and selective attention were subserved in part by common areas with limited neural processing capacity, activation in these areas under conditions of joint demand on both processes should reach a plateau or at least be less than additive, as reflected in a statistical interaction between attention and WM. Conversely, we expected to find an additive increase in BOLD activation under simultaneous WM and attentional demands in regions whose processing capacity was not exceeded. The BOLD signal in these overlap regions should increase to the same degree with WM load under low and high attentional demand. It was important to observe this pattern in at least some brain areas in order to rule out the possibility that the capacity constrained pattern observed in other areas was an effect of hemodynamic saturation or time spent on task components.

#### Common activation for visual attention and WM encoding

Overlapping activation for attention-demanding visual search and encoding into visual WM was observed in distributed posterior and frontal regions. Consistent with our hypotheses a subset of these regions, in the right prefrontal cortex and bilateral insula, showed an additive increase in BOLD activation associated with increased WM load and attentional demand. These results are in agreement with the view that the processes underlying attention-demanding visual search and the encoding into visual WM require access to common neural and cognitive resources. The additive increase in BOLD activation suggests that the demands on these frontal regions were well within their processing limits even in the condition where high WM load was combined with difficult search. Conversely, our analysis revealed an interaction effect between the two task manipulations for visual, parietal and



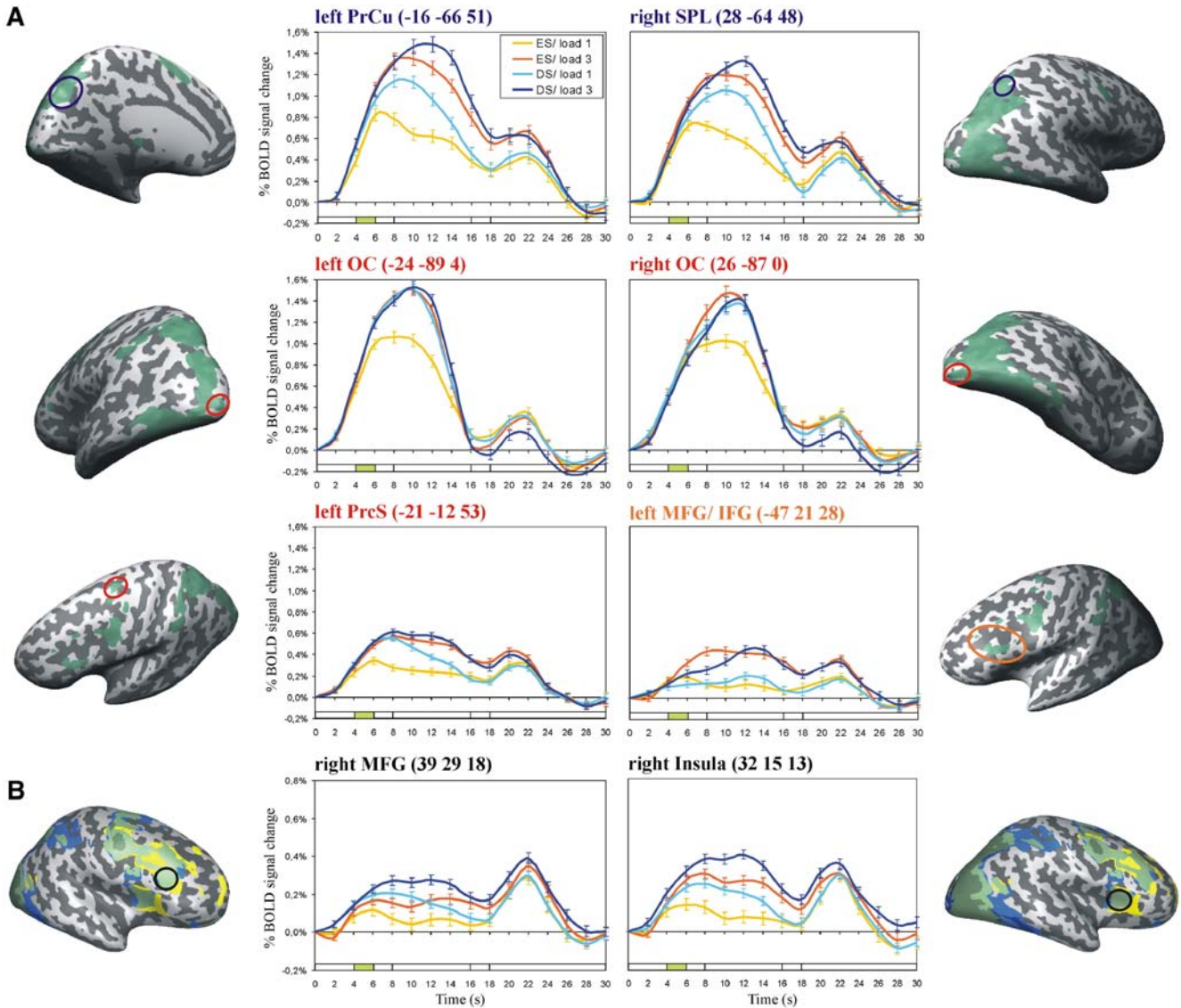


Fig. 4. Averaged time courses of the BOLD response in the four conditions. (A) Statistical group maps of the interaction contrast of search difficulty  $\times$  WM load during late encoding are shown. The maps are projected on inflated surface reconstructions of the MNI template brain (dark green). During encoding time courses indicated a smaller increase in BOLD signal with increasing WM load for DS vs. ES in parietal regions (purple circles; PrCu: precuneus, SPL: superior parietal lobule). In the occipital cortex (OC) and the PrcS the BOLD response did not exceed a plateau of activation that was reached already with load 3/ES and load 1/DS (red circles). A delayed WM load effect for DS vs. ES was revealed in the left MFG and IFG (orange circle). (B) Statistical maps of the contrasts DS vs. ES (yellow), WM load 3 vs. 1 (blue), and the significant 2-way interaction of search difficulty  $\times$  WM load (black) are shown. Regions in the right MFG and insula (black circles) showed an additive increase in activation with increased WM load and search difficulty. Bars represent standard errors of the mean.

premotor cortex. Activation increased from WM load 1 to WM load 3 but this increase was significantly smaller in the difficult compared to the easy search condition. In contrast, activation associated with increased WM load in the left PFC was delayed rather than reduced under high attentional demand. These results indicate that competition for processing resources that are shared by the WM and attention systems can lead to a severe limitation of neural processing capabilities.

The brain areas mediating these common processing limitations of visual WM and attention include regions that are classically considered to support goal-directed visuospatial attention (Kanwisher and Wojciulik, 2000; Corbetta and Shulman, 2002; Pessoa et al., 2003) and have been implicated in the capacity limitation of

visual WM (Linden et al., 2003; Todd and Marois, 2004; Marois and Ivanoff, 2005; Xu and Chun, 2006). Indeed, a survey of the neural substrates that support top-down mechanisms for visual WM showed a striking degree of overlap with those of selective attention (Pessoa and Ungerleider, 2004). The design characteristics of our combined task allowed us to assign functional consequences to the overlap in activation by testing for interactions between the two task components which were found in a subset of the brain regions that supported both attentional selection and WM encoding. Thus, our demonstration of interference between the processes involved in attention-demanding visual search and WM encoding strongly suggests that the two cognitive domains tap into common neural resources.

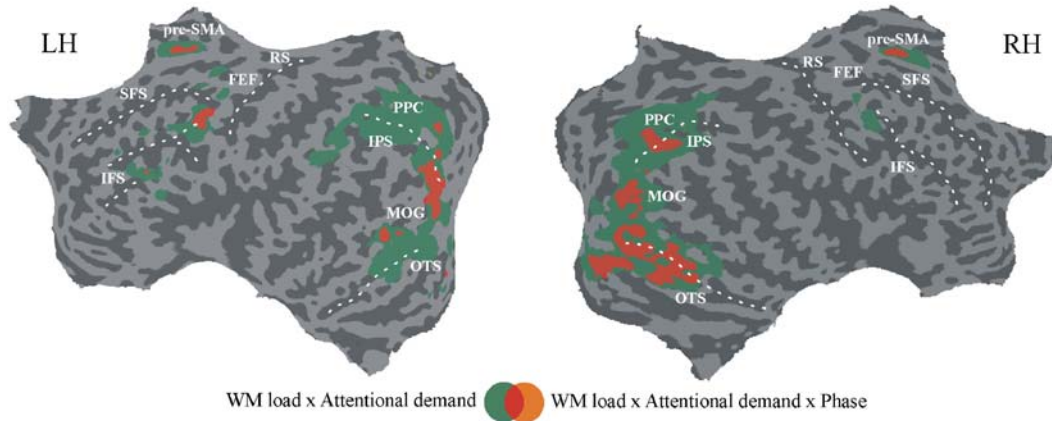


Fig. 5. Influence of search speed on the interaction of search difficulty  $\times$  WM load. Results of the 3-way interaction analysis between search difficulty (DS vs. ES), WM load (3 vs. 1) and encoding phase (E3 vs. E1) are shown superimposed in orange on the results of the 2-way interaction of search difficulty  $\times$  WM load (dark green). Activations are those that exceeded a whole-brain false discovery rate threshold of  $q(\text{FDR}) < 0.05$ . Encoding phase E1: 0–2 s, encoding phase E3: 4–6 s.

#### Evidence for a neural bottleneck of visual attention and WM encoding?

Capacity limits of information processing traditionally have been interpreted in terms of bottlenecks that occur if the same two cognitive operations act upon a single capacity-limited channel (Broadbent, 1958). As a result, one or both operations will be delayed or otherwise impaired (Pashler, 1994; Jolicoeur and Dell'Acqua, 1999; Sigman and Dehaene, 2005). It has been shown that processing bottlenecks can operate at different stages in the flow of information from perception to memory and action (Pashler, 1998; Marois and Ivanoff, 2005). With regard to the present findings we thus propose that the distributed regions in the posterior, but not prefrontal cortex form a neural bottleneck for joint demand on attention and WM resources during the stage of WM encoding.

On the basis of the present data we cannot decide whether the bottleneck reflects capacity limitations at a particular set of regions or constraints of the capacity for cooperation among multiple regions. Nevertheless, we show that event-related fMRI can detect interactions in activity patterns in response to increased attentional

and WM demands within distributed cortical regions. Our results indicate common capacity limitations for visual WM and attention in the occipito-temporal and posterior parietal cortex, the PrcS, and the pre-SMA in both hemispheres. This limitation was manifested in a reduced WM load effect under conditions of difficult versus easy visual search and was pronounced most strongly in early and higher visual areas and in the left dorsal PrcS.

It might be argued that the plateau of activation that was already reached with load 3/ES and load 1/DS was a result of a hemodynamic saturation of the neurovascular system. BOLD activation in visual areas showed an increase of up to 1.5% signal change and in the left dorsal PrcS a plateau of activation was reached at 0.6% signal change. This activation is unlikely to have reached the physiological plateau because checkerboard stimulation with similar scanning parameters can lead to BOLD signal changes of up to 4% in the occipital cortex (Uludağ et al., 2004) which is about three-fold larger activation than the presently observed saturation point. Moreover, several regions associated with an overlap in activation but no interaction showed a further increase in BOLD activity from load 1/DS to load 3/DS and from load 3/ES to load 3/DS (Fig. 4B). Such an additive increase appeared in regions adjacent to those

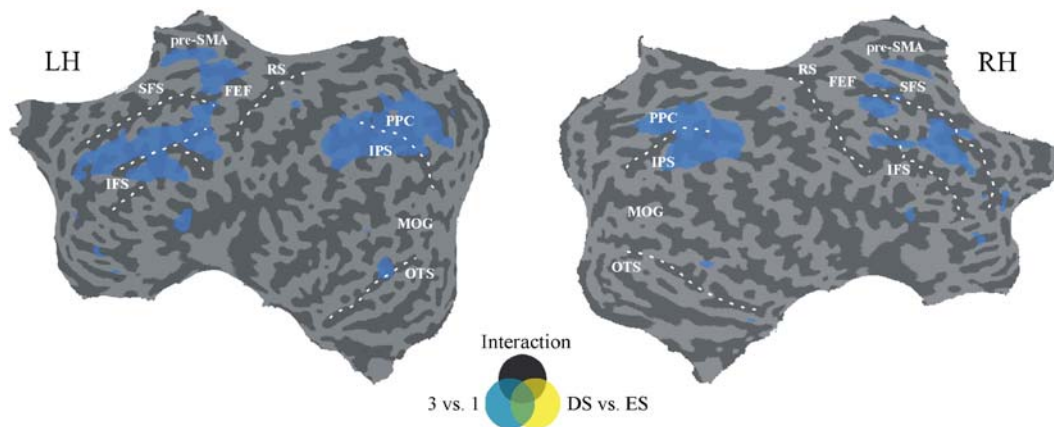


Fig. 6. Group results for the late delay predictor (12–14 s). Significant activations were found only for the WM load contrast (load 3 vs. load 1) (blue). Activations are those exceeding a whole-brain false discovery rate threshold of  $q(\text{FDR}) < 0.05$ .

showing a strong plateau effect, for instance in the right MFG and bilateral insula, which suggests that the latter effect also resulted from differential processing induced by the task manipulations rather than from hemodynamic saturation.

It furthermore does not seem plausible that the plateau effect observed in the visual cortex is owed to limitations on perceptual rather than memory processes. It has been proposed that in inefficient visual search tasks when targets and distractors are highly similar attention is shifted serially from one item or one group of items to the next (Treisman and Gormican, 1988). At most, one group might comprise about 4 items (Pylyshyn and Storm, 1988; Cavanagh and Alvarez, 2005). As participants were not informed about the number of targets presented in the upcoming array they had to serially scan the entire array of nine items in order to find the single target in the difficult search condition. In contrast, in the easy search condition they immediately focused the target items. Thus in load 3/ES only three (or one group of three items), as opposed to nine items (or three groups of three items) in load 1/DS, had to be processed. If memory processing had not played a role, we would have expected a further increase in activation for load 1/DS compared to load 3/ES due to a higher perceptual load which, however, was not observed. Thus, the activation pattern in the visual cortex was not solely a result of limitations on perceptual processing but rather reflected both perceptual- and WM-related processing.

In the present task, the two search conditions differed in the degree of search efficiency as indicated in the pilot behavioral study by slower processing times (about 4 s) in the difficult compared to the easy search condition. However, in light of the behavioral performance in the fMRI experiment and the absence of search difficulty effects on the delay activity it is unlikely that insufficient time available for WM encoding in the most demanding condition produced the smaller effect of WM load in the difficult vs. the easy search condition. Response accuracy and RTs at test were equally high in the two search conditions and delay activity increased to the same degree from WM load 1 to load 3, irrespective of search difficulty. Moreover, the additive increase in activation with high WM load and difficult search in several regions rules out that the observed interaction effect was owed to incomplete encoding or prolonged search in the more demanding conditions (load 3/DS, load 3/ES and load 1/DS) compared to the less demanding condition (load 1/ES). Taken together, these results indicate that even under difficult visual search participants efficiently engaged into the process of encoding into WM, which is a prerequisite for successful WM maintenance.

The influence of temporal differences across search conditions was further addressed in two subsequent analyses. Taking the faster search process in the easy search condition into account by contrasting DS/late encoding (4–6 s after stimulus onset) versus ES/early encoding (0–2 s after stimulus onset) we replicated the effect of attentional demand that was observed during the late encoding phase in those regions that showed strong plateau effects associated with processing limitations during encoding (left dorsal PrC and bilateral visual cortex) (see Fig. S1 and Supplementary analysis 2). Moreover, 3-way interaction analyses between the factors search difficulty, WM load and encoding phase did not yield significant activation in those regions either (Fig. 5). We are aware that caution is warranted in interpreting non-effects because of potentially insufficient statistical power. However, the BOLD response functions which showed little differences in latency or

slope across conditions in these regions (Fig. 4A) suggest that the plateau effects were not a result of fast versus slow visual search.

#### *Selective activations for visual attention and WM encoding*

As participants applied attentional and WM processes to the same stimulus displays we were able to identify the brain areas that were selectively responsive to either WM encoding or attentional demand. Areas specifically sensitive to WM load appeared in the left lateral PFC, the left anterior inferior parietal lobule, and bilaterally in the inferior temporal cortex. Interestingly, the prefrontal areas showed a time shift in activation associated with the increase in WM load between the easy and the difficult search condition (Fig. 4A). The delay of about 4 s reflected accurately the delay in encoding times estimated in the pilot behavioral study. As attention-demanding visual search and WM encoding shared a large portion of their neural resources in posterior regions we propose that the delayed WM load-related activation in the left PFC was a consequence of this neural bottleneck. In the light of equal memory performance at test across search conditions, we propose that this delay in activation reflects a mechanism that allowed participants to compensate for the common demands on limited neural resources shared by attention and WM processes in the posterior cortex. The interplay between the PFC and posterior regions was not in the direct focus of the present study. Nevertheless, the present data indicate that successful encoding into visual WM requires joint processing across encoding-selective areas and areas that are also called upon by demands on selective attention. The availability of neural resources mediating selective attention, thus, seems to be a critical factor for constraining the process of encoding information into visual WM.

Interestingly, the PFC showed a hemispheric asymmetry with left MFG and IFG selectively responsive to WM load and right MFG and IFG selectively responsive to attentional demand which might point to a functional dissociation of the PFC (see Supplementary analysis 1 and Table S1). In line with this finding, prefrontal hemispheric specialization has been reported in previous imaging studies showing right-dominant activation during conditions of inefficient visual search (Pollmann and von Cramon, 2000; Nobre et al., 2003) and visuospatial orienting (Rosen et al., 1999). WM for non-spatial material such as objects, colors and faces has been associated particularly with the left PFC in contrast to spatial material which is represented predominantly in the right hemisphere (D'Esposito et al., 1998; Fletcher and Henson, 2001; Munk et al., 2002; Manoach et al., 2004; Mohr et al., 2006). Therefore, the left-hemispheric dominance of WM load-related activation in our task might reflect content-specific encoding processes.

#### *An attention-based model of visual WM encoding*

A crucial role of selective attention for WM maintenance has been well established (Awh et al., 1998; Awh and Jonides, 2001; Jha, 2002; Postle et al., 2004; Lepsien and Nobre, in press). The present study focused on the encoding of objects into WM and our findings suggest that an attention-based model applies to the encoding period as well.

Why would attentional mechanisms be needed during the encoding of information into visual WM? Complex objects, as used in the present task and as we usually encounter them in our everyday experience, consist of multiple parts, each with its own features.



Different features are bound together into integrated objects by means of focused attention (Treisman and Gelade, 1980). We suggest that in the context of WM, distinct regions in the visual cortex serve as simple parallel feature stores. These stores are modulated by attentional mechanisms (Awh and Jonides, 2001; Jha, 2002; Postle et al., 2004; Lepsien and Nobre, in press) that integrate the distributed information into unified object representations (Wheeler and Treisman, 2002). These attentional modulations seem to be subserved by parietal and premotor regions (Kanwisher and Wojciulik, 2000; Corbetta and Shulman, 2002; Pessoa et al., 2003). Therefore, the need for integration of information might be one possibility that determines the interference between visual WM and attention demands in posterior parts of the cortex.

The PFC was not part of the network that was involved in the joint demand on attention and WM resources. Prefrontal activation has been linked to a variety of control processes (Miller and Cohen, 2001) such as selection (Rowe et al., 2000), monitoring and transformation of information held in WM (Petrides, 2000; Bor et al., 2003) or mediation of interference (Postle, 2005). In addition, PFC responds to WM load beyond the capacity of the parietal–premotor network (Linden et al., 2003). Therefore, WM load-selective activation in the PFC might fit within the framework postulating that this brain region subserves extra-mnemonic processes of top–down control over posterior regions where information is actually stored (Curtis and D'Esposito, 2003; Postle, 2006).

The finding of common capacity-limited neural mechanisms shared between visual WM encoding and attention does not necessarily imply that the capacity limit of visual WM is fully reducible to that of attention (Fougnie and Marois, 2006). Cognitive processes mediated by the PFC likely have their own capacity limitations as well, which may specifically constrain the maintenance and manipulation of information stored in visual WM. Also, processes specifically associated with the retrieval of information from WM might be subject to their own specific capacity limitations. Yet, the present results illustrate that one major bottleneck of information processing arises from the common demands on neural resources shared between visual WM and attention during the encoding stage.

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### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2007.03.007.

### References

Atkinson, R.C., Shiffrin, R.M., 1968. Human memory: a proposed system and its control processes. In: Spence, K.W., Spence, J.T. (Eds.), *The*

- Psychology of Learning and Motivation: Advances in Research and Theory. Academic Press, New York, pp. 89–195.
- Awh, E., Jonides, J., 2001. Overlapping mechanisms of attention and spatial working memory. *Trends Cogn. Sci.* 5, 119–126.
- Awh, E., Jonides, J., Reuter-Lorenz, P.A., 1998. Rehearsal in spatial working memory. *J. Exp. Psychol. Hum. Percept. Perform.* 24, 780–790.
- Awh, E., Vogel, E.K., Oh, S.H., 2006. Interactions between attention and working memory. *Neuroscience* 139, 201–208.
- Baddeley, A.D., 1993. Working memory or working attention? In: Baddeley, A.D., Weiskrantz, L. (Eds.), *Attention: Selection, Awareness, and Control*. A Tribute to Donald Broadbent. Oxford Univ. Press, Oxford, pp. 152–170.
- Bledowski, C., Cohen Kadosh, K., Wibrall, M., Rahm, B., Bittner, R.A., Hoechstetter, K., Scherg, M., Maurer, K., Goebel, R., Linden, D.E.J., 2006. Mental chronometry of working memory retrieval: a combined functional magnetic resonance imaging and event-related potentials approach. *J. Neurosci.* 26, 821–829.
- Bor, D., Duncan, J., Wiseman, R.J., Owen, A.M., 2003. Encoding strategies dissociate prefrontal activity from working memory demand. *Neuron* 37, 361–370.
- Broadbent, D.E., 1958. *Perception and Communication*. Pergamon, London.
- Bundesen, C., 1990. A theory of visual attention. *Psychol. Rev.* 97, 523–547.
- Cavanagh, P., Alvarez, G.A., 2005. Tracking multiple targets with multifocal attention. *Trends Cogn. Sci.* 9, 349–354.
- Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. *Nat. Rev., Neurosci.* 3, 201–215.
- Corbetta, M., Kincade, J.M., Shulman, G.L., 2002. Neural systems for visual orienting and their relationships to spatial working memory. *J. Cogn. Neurosci.* 14, 508–523.
- Courtney, S.M., Ungerleider, L.G., Keil, K., Haxby, J.V., 1997. Transient and sustained activity in a distributed neural system for human working memory. *Nature* 386, 608–611.
- Cowan, N., 1988. Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychol. Bull.* 104, 163–191.
- Cowan, N., 1998. Visual and auditory working memory capacity. *Trends Cogn. Sci.* 2, 77–78.
- Cowan, N., 2001. The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *Behav. Brain Sci.* 24, 87–114.
- Culham, J.C., Cavanagh, P., Kanwisher, N.G., 2001. Attention response functions: characterizing brain areas using fMRI activation during parametric variations of attentional load. *Neuron* 32, 737–745.
- Curtis, C.E., D'Esposito, M., 2003. Persistent activity in the prefrontal cortex during working memory. *Trends Cogn. Sci.* 7, 415–423.
- D'Esposito, M., Aguirre, G.K., Zarahn, E., Ballard, D., Shin, R.K., Lease, J., 1998. Functional MRI studies of spatial and nonspatial working memory. *Cogn. Brain Res.* 7, 1–13.
- Duncan, J., Humphreys, G.W., 1989. Visual search and stimulus similarity. *Psychol. Rev.* 96, 433–458.
- Duncan, J., Ward, R., Shapiro, K., 1994. Direct measurement of attentional dwell time in human vision. *Nature* 369, 313–315.
- Fletcher, P.C., Henson, R.N., 2001. Frontal lobes and human memory: insights from functional neuroimaging. *Brain* 124, 849–881.
- Fougnie, D., Marois, R., 2006. Distinct capacity limits for attention and working memory. *Psychol. Sci.* 17, 526–534.
- Friston, K.J., Fletcher, P., Josephs, O., Holmes, A., Rugg, M.D., Turner, R., 1998. Event-related fMRI: characterizing differential responses. *NeuroImage* 7, 30–40.
- Genovese, C., Lazar, N., Nichols, T., 2002. Thresholding of statistical maps in functional neuroimaging using the false discovery. *NeuroImage* 15, 870–878.
- Jha, A.P., 2002. Tracking the time-course of attentional involvement in spatial working memory: an event-related potential investigation. *Cogn. Brain Res.* 15, 61–69.
- Joliceur, P., Dell'Acqua, R., 1998. The demonstration of short-term consolidation. *Cogn. Psychol.* 36, 138–202.



- Jolicœur, P., Dell'Acqua, R., 1999. Attentional and structural constraints on visual encoding. *Psychol. Res.* 62, 154–164.
- Kanwisher, N., Wojciulik, E., 2000. Visual attention: insights from brain imaging. *Nat. Rev., Neurosci.* 1, 91–100.
- LaBar, K.S., Gitelman, D.R., Parrish, T.B., Mesulam, M.M., 1999. Neuroanatomic overlap of working memory and spatial attention networks: a functional MRI comparison within subjects. *NeuroImage* 10, 695–704.
- Lepsien, J., Nobre, A.C., in press. Attentional modulation of object representations in working memory. *Cereb. Cortex*, (2006 Nov 10, Epub ahead of print).
- Lepsien, J., Griffin, I.C., Devlin, J.T., Nobre, A.C., 2005. Directing spatial attention in mental representations: interactions between attentional orienting and working-memory load. *NeuroImage* 26, 733–743.
- Linden, D.E.J., Bittner, R.A., Muckli, L., Waltz, J.A., Kriegeskorte, N., Goebel, R., Singer, W., Munk, M.H.J., 2003. Cortical capacity constraints for visual working memory: dissociation of fMRI load effects in a fronto-parietal network. *NeuroImage* 20, 1518–1530.
- Logie, R.H., 1995. *Visuo-Spatial Working Memory*. Erlbaum, Hove.
- Luck, S.J., Vogel, E.K., 1997. The capacity of visual working memory for features and conjunctions. *Nature* 390, 279–281.
- Manoach, D.S., White, N.S., Lindgren, K.A., Heckers, S., Coleman, M.J., Dubal, S., Holzman, P.S., 2004. Hemispheric specialization of the lateral prefrontal cortex for strategic processing during spatial and shape working memory. *NeuroImage* 21, 894–903.
- Marois, R., Ivanoff, J., 2005. Capacity limits of information processing in the brain. *Trends Cogn. Sci.* 9, 296–305.
- Miller, E.K., Cohen, J.D., 2001. An integrative theory of prefrontal function. *Annu. Rev. Neurosci.* 24, 167–202.
- Mohr, H., Goebel, R., Linden, D.E.J., 2006. Content- and task-specific dissociations of frontal activity during maintenance and manipulation in visual working memory. *J. Neurosci.* 26, 4465–4471.
- Munk, M.H., Linden, D.E.J., Muckli, L., Lanfermann, H., Zanella, F.E., Singer, W., Goebel, R., 2002. Distributed cortical systems in visual short-term memory revealed by event-related functional magnetic resonance imaging. *Cereb. Cortex* 12, 866–876.
- Nieder, A., 2004. The number domain – can we count on parietal cortex? *Neuron* 44, 407–409.
- Nobre, A.C., Coull, J.T., Walsh, V., Frith, C.D., 2003. Brain activations during visual search: contributions of search efficiency versus feature binding. *NeuroImage* 18, 91–103.
- Nobre, A.C., Coull, J.T., Maquet, P., Frith, C.D., Vandenberghe, R., Mesulam, M.M., 2004. Orienting attention to locations in perceptual versus mental representations. *J. Cogn. Neurosci.* 16, 363–373.
- Oh, S.H., Kim, M.S., 2004. The role of spatial working memory in visual search efficiency. *Psychon. Bull. Rev.* 11, 275–281.
- Pashler, H., 1988. Familiarity and visual change detection. *Percept. Psychophys.* 44, 369–378.
- Pashler, H., 1994. Dual-task interference in simple tasks: data and theory. *Psychol. Bull.* 116, 220–244.
- Pashler, H.E., 1998. *The Psychology of Attention*. MIT Press, Cambridge.
- Pessoa, L., Ungerleider, L.G., 2004. Top-down mechanisms for working memory and attentional processes. In: Gazzaniga, M.S. (Ed.), *The New Cognitive Neurosciences*. MIT Press, Cambridge, pp. 919–930.
- Pessoa, L., Gutierrez, E., Bandettini, P.A., Ungerleider, L.G., 2002. Neural correlates of visual working memory: fMRI amplitude predicts task performance. *Neuron* 35, 975–987.
- Pessoa, L., Kastner, S., Ungerleider, L.G., 2003. Neuroimaging studies of attention: from modulation of sensory processing to top-down control. *J. Neurosci.* 23, 3990–3998.
- Petrides, M., 2000. The role of the mid-dorsolateral prefrontal cortex in working memory. *Exp. Brain Res.* 133, 44–54.
- Phillips, W.A., 1974. On the distinction between sensory storage and short-term visual memory. *Percept. Psychophys.* 16, 283–290.
- Palmer, J., 1990. Attentional limits on the perception and memory of visual information. *J. Exp. Psychol. Hum. Percept. Perform.* 16, 332–350.
- Pollmann, S., von Cramon, D.Y., 2000. Object working memory and visuospatial processing: functional neuroanatomy analyzed by event-related fMRI. *Exp. Brain Res.* 133, 12–22.
- Postle, B.R., 2005. Delay-period activity in the prefrontal cortex: one function is sensory gating. *J. Cogn. Neurosci.* 17, 1679–1690.
- Postle, B.R., 2006. Working memory as an emergent property of the mind and brain. *Neuroscience* 139, 23–38.
- 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. *Cogn. Brain Res.* 20, 194–205.
- Pylyshyn, Z.W., Storm, R.W., 1988. Tracking multiple independent targets: evidence for a parallel tracking mechanism. *Spat. Vis.* 3, 179–197.
- Ranganath, C., DGutis, J., D'Esposito, M., 2004. Category-specific modulation of inferior temporal activity during working memory encoding and maintenance. *Brain Res. Cogn. Brain Res.* 20, 37–45.
- Rao, S.C., Rainer, G., Miller, E.K., 1997. Integration of what and where in the primate prefrontal cortex. *Science* 276, 821–824.
- Rosen, A.C., Rao, S.M., Caffarra, P., Scaglioni, A., Bobholz, J.A., Woodley, S.J., Hammeke, T.A., Cunningham, J.M., Prieto, T.E., Binder, J.R., 1999. Neural basis of endogenous and exogenous spatial orienting: a functional MRI study. *J. Cogn. Neurosci.* 11, 135–152.
- Rowe, J.B., Toni, I., Josephs, O., Frackowiak, R.S., Passingham, R.E., 2000. The prefrontal cortex: response selection or maintenance within working memory? *Science* 288, 1656–1660.
- Schmidt, B.K., Vogel, E.K., Woodman, G.F., Luck, S.J., 2002. Voluntary and automatic attentional control of visual working memory. *Percept. Psychophys.* 64, 754–763.
- Scholl, B.J., 2001. Objects and attention: the state of the art. *Cognition* 80, 1–46.
- Sigman, M., Dehaene, S., 2005. Parsing a cognitive task: a characterization of the mind's bottleneck. *PLoS Biol.* 3, 334–349.
- Smyth, M.M., Scholey, K.A., 1994. Interference in immediate spatial memory. *Mem. Cogn.* 22, 1–13.
- Todd, J.J., Marois, R., 2004. Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature* 428, 751–754.
- Treisman, A., Gelade, G., 1980. A feature-integration theory of attention. *Cogn. Psychol.* 12, 97–136.
- Treisman, A., Gormican, S., 1988. Feature analysis in early vision: evidence from search asymmetries. *Psychol. Rev.* 95, 15–48.
- Uludağ, K., Dubowitz, D.J., Yoder, E.J., Restom, K., Liu, T.T., Buxton, R.B., 2004. Coupling of cerebral blood flow and oxygen consumption during physiological activation and deactivation measured with fMRI. *NeuroImage* 23, 148–155.
- Vogel, E.K., Machizawa, M.G., 2004. Neural activity predicts individual differences in visual working memory capacity. *Nature* 428, 748–751.
- Wheeler, M.E., Treisman, A.M., 2002. Binding in short-term visual memory. *J. Exp. Psychol. Gen.* 131, 48–64.
- Woodman, G.F., Luck, S.J., 2004. Visual search is slowed when visuospatial working memory is occupied. *Psychon. Bull. Rev.* 11, 269–274.
- Xu, Y., Chun, M.M., 2006. Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature* 440, 91–95.
- Zarahn, E., Aguirre, G., D'Esposito, M., 1997. A trial-based experimental design for fMRI. *NeuroImage* 6, 122–138.