Modality effects in verbal working memory: differential prefrontal and parietal responses to auditory and visual stimuli

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The neural bases of verbal (nonspatial) working memory (VWM) have been primarily examined using visual stimuli. Few studies have investigated the neural bases of VWM using auditory stimuli, and fewer have explored modality differences in VWM. In this study, we used functional magnetic resonance imaging (fMRI) to examine similarities and differences between visual VWM (vis-VWM) and auditory VWM (aud-VWM) utilizing identical stimuli and a within-subjects design. Performance levels were similar in the two modalities and there was extensive overlap of activation bilaterally in the dorsolateral and ventrolateral prefrontal cortex (DLPFC and VLPFC), intraparietal sulcus, supramarginal gyrus and the basal ganglia. However, a direct statistical comparison revealed significant modality differences: the left posterior parietal cortex, primarily along the intraparietal sulcus, showed greater responses during vis-VWM whereas the left dorsolateral prefrontal cortex showed greater responses during aud-VWM. No such differences were observed in the right hemisphere. Other modality differences in VWM were also observed, but they were associated with relative decreases in activation. In particular, we detected bilateral suppression of the superior and middle temporal (auditory) cortex during vis-VWM, and of the occipital (visual) cortex during aud-VWM, thus suggesting that cross-modal inhibitory processes may help to provide preferential access to high-order heteromodal association areas. Taken together, our findings suggest that although similar prefrontal and parietal regions are involved in aud-VWM and vis-VWM, there are important modality differences in the way neural signals are generated, processed and routed during VWM.
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Introduction

Working memory (WM), the ability to maintain and manipulate information during a short interval, has been widely used to investigate the basic operations underlying higher brain function

(Baddeley, 1997; Goldman-Rakic, 1999). The component processes involved in WM—encoding, rehearsal, storage and executive processes on the contents of stored memory—characterize key cognitive operations of the human brain. The highly influential Baddeley–Hitch model (Baddeley, 1986; Baddeley and Hitch, 1974) has proposed a system that consists of a central executive, an attentional controller aided by two subsidiary systems—the phonological loop, capable of holding verbal information, and the visuospatial sketchpad, which performs a similar function for spatial information. This model has been recently extended to include a fourth component—an episodic buffer that provides temporary storage of information held in a multimodal code, which is capable of binding information from the subsidiary systems, and from long-term memory, into a unitary episodic representation (Baddeley, 2000). The two subsidiary systems are thought to form active storage buffers that combine information from sensory input and from the central executive. Although the Baddeley–Hitch model has been influential in our thinking about cognitive processes involved in WM, its neural basis remains poorly specified. In particular, very little information is currently available about the extent to which verbal working memory (VWM) processes are dependent on the modality of sensory input.

The aim of the present study is to examine similarities and differences in the processing of VWM for aurally and visually presented stimuli. Most of our understanding of the neural networks underlying VWM has been based on studies using visually presented stimuli (vis-VWM; see Smith and Jonides, 1998 for a review). In contrast, few studies have examined the neural basis of auditory VWM (aud-VWM), and fewer still have directly examined modality differences using similar tasks in a within-subjects design.

The distinction between aud-VWM and vis-VWM is an important one, with implications for both theoretical and experimental research into the neural processes underlying working memory. In particular, an examination of similarities and differences in processing of different types of stimuli can provide insights into the internal representations of stimuli in working memory. Lesion studies have provided some evidence for modality-specific deficits (Basso et al., 1982; Shallice and Warrington, 1977; Warrington and Shallice, 1969, 1972), leading to the suggestion that short-term memory processing in the two modalities is mediated by separate streams that have different properties and capabilities (Penney,

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1989). Behavioral research has pointed to differences in auditory and visual short-term memory processing (Allport et al., 1972; Kroll et al., 1970; Penney, 1989) but the task conditions in which modality differences can be elicited are complex. While some researchers have suggested an auditory bias (i.e. better performance in auditory, compared to visual, VWM) (Penney, 1989), others have shown that an auditory bias can be easily created with simple perturbations to the task (Beaman, 2002). Although the precise nature of modality-specific differences is still being resolved in behavioral studies, these findings, taken together, nevertheless suggest that there are important differences in the internal representations of auditory and visual stimuli in VWM.

Despite its potential significance, to date only two brain imaging studies have examined differences between aud-VWM and vis-VWM. A PET study by Schumacher et al. (1996) showed common activation of bilateral SMA [Broadmann Area (BA) 6], bilateral superior (BA 7) and posterior parietal cortex (BA 40), and right cerebellum during 2-back aud-VWM and vis-VWM tasks. A direct comparison of the two modalities revealed few differences: auditory, compared to visual, VWM showed greater activation in Broca's area, whereas visual, compared to auditory, VWM did not reveal greater activation in any brain region. Schumacher et al. (1996) interpreted these findings as providing evidence for relatively minor quantitative differences in encoding, and further suggested that VWM processing is amodal. However, Ruchkin et al. (1997a) found significant differences in amplitude and timing of event-related potentials (ERPs) elicited during aud-VWM and vis-VWM. Left frontal negative waves indexing retention and rehearsal operations were triggered earlier and were more long lasting during aud-VWM. On the other hand, posterior regions showed larger evoked potentials for visual stimuli (see also Lang et al., 1992). Thus, although the PET study by Schumacher et al. (1996) suggests that VWM processing is primarily amodal, behavioral and ERP studies have provided evidence for modality-specific differences in VWM processing in both prefrontal and posterior brain regions. A third related study used PET to measure regional cerebral blood flow (rCBF) during performance of 1-back auditory and visual WM tasks, although the primary focus of the study was the examination of multimodal interference (Klingberg, 1998; Klingberg et al., 1996). Compared to the two other studies (Ruchkin et al., 1997a; Schumacher et al., 1996), Klingberg et al.'s studies focused on nonverbalizable, pitch and luminance based, stimuli in the two modalities, a design we explicitly avoided here. Interestingly, none of these studies has conducted a direct statistical comparison between effects in the two modalities, so that amodal effects, if any, were never rigorously examined.

To help resolve these discrepancies in the literature, we used functional magnetic resonance imaging (fMRI) to examine VWM processing, with identical experimental paradigms and similar auditory and visual stimuli. We examined the extent to which the working memory networks in the two modalities overlap, whether there are any gross (qualitative) modality differences and whether there are quantitative differences within brain areas that are activated by both modalities. One focus of our work was to resolve divergent findings between the two published PET (Schumacher et al., 1996) and ERP (Ruchkin et al., 1997a) studies. Towards this end, a close correspondence was maintained between auditory and visual stimuli, analogous to these PET and ERP studies so that differences between modalities could be attributable only to differences in the way auditory and visual codes are used in the context of VWM.

We hypothesized that the phonological loop would be engaged by both auditory and visual stimuli. Correspondingly, we predicted activation of similar regions of the posterior parietal cortex. We further hypothesized that it would be necessary for visual stimuli to be transformed to a phonological format, and then entered into a phonological store through articulatory rehearsal. Auditory stimuli, however, do not have to undergo such a transformation as they are more automatically encoded into a phonological format (Shallice and Vallar, 1990). We therefore predicted that brain regions involved in making the transformation to the phonological store would show greater activation during vis-VWM, compared to aud-VWM. Alternatively, it might also be possible that visual and auditory stimuli are handled by entirely distinct processing streams in the association cortex, in which case we would expect to find distinct, neuroanatomically segregated patterns of activation.

Materials and methods

Subjects

Fourteen healthy right-handed subjects (7 females, 7 males; ages: 18–32 years) participated in this study after giving written informed consent. Handedness was assessed using the Edinburgh test (Oldfield, 1971). The human subjects committee at Stanford University School of Medicine approved all protocols used in this study.

Experimental procedure

Subjects performed two identical VWM experiments in the scanner: (i) an aud-VWM task, in which stimuli were presented aurally and (ii) a vis-VWM task, in which stimuli were presented visually. The order of experiments was randomized across subjects. Each experiment consisted of 12 alternating VWM and control epochs, each lasting 28 s. The order of the VWM and control epochs was counter-balanced across subjects. Each epoch began with a 4-s instruction about the task they should perform in the next 24 s. In each epoch, 12 stimuli were presented: each stimulus lasted 500 ms with an interstimulus interval of 2 s. The stimuli were single-digit numbers (0–9), presented at the center of a screen placed in front of the subject in the case of vis-VWM or binaurally in the case of aud-VWM. In the VWM epochs, subjects performed a 2-back task; they were instructed to press a button with their right index finger if the number currently on display was the same as the number presented two trials back and to press another button with the right middle finger if it was not. In the control epochs, subjects were instructed to respond with their right index finger if the number currently on display was "3", and with their right middle finger if it was not. Two 30-s "resting" baseline epochs were acquired before and after the VWM and control epochs. Auditory and visual stimuli were presented using a custom-built, magnet compatible, audio-visual projection system (Resonance Technology, CA).

Behavioral data analysis

Accuracy and reaction time (RT) for the VWM and control conditions were measured. Accuracy was measured as the percentage of trials (match and nonmatch) in which the subject responded correctly with the appropriate button press. RTs were measured

from the time of stimulus onset. Accuracy and RT, for the correct responses, were analyzed using a 2 × 2 Analysis of Variance (ANOVA) with factors: Modality (Auditory, Visual) and Task (VWM, control).

fMRI acquisition

Images were acquired on a 1.5-T GE Signa scanner with Echospeed gradients using a standard whole head coil. A custom-built head holder was used to prevent head movement. Twenty-seven axial slices (4-mm thick, 0.5-mm skip, acquisition voxel size: 3.75 × 3.75 × 4.5 mm) parallel to the anterior and posterior commissure covering the whole brain were imaged with a temporal resolution of 2 s using a T2* weighted gradient echo spiral pulse sequence (TR = 2000 ms; TE = 40 ms; flip angle = 89°; and 1 interleave) (Glover and Lai, 1998). The field of view was 200 mm and the effective inplane spatial resolution was 3.25 mm. To aid in localization of functional data, a high-resolution T1-

weighted spoiled grass gradient recalled (SPGR) 3D MRI sequence with the following parameters was used: TR = 35 ms; TE = 6 ms; flip angle = 45°; 24-cm field of view; 124 slices in coronal plane; 256 × 192 matrix.

fMRI data analysis

fMRI data were pre-processed using SPM99 (http://www.fil.ion.ucl.ac.uk/spm). Images were corrected for movement using least square minimization without higher-order corrections for spin history, and normalized to stereotaxic Talairach coordinates (Talairach and Tournoux, 1988). Images were then resampled every 2 mm (voxel size after processing: 2 × 2 × 2 mm) using sinc interpolation and smoothed with a 4-mm Gaussian kernel to decrease spatial noise. All trials (with correct and incorrect responses) have been included in the analyses. Statistical analysis was performed on individual and group data using the general linear model (box-car model) and the theory of

Table 1
Brain areas that show significant activation during (i) auditory WM, (ii) visual WM, and brain areas that show greater activation during (iii) auditory, compared to visual, WM and (iv) visual, compared to auditory, WM

	Corrected P value	Number of voxels	Z score	Peak Talairach coordinates		
(i) Auditory (WM–control)						
L superior and middle frontal gyrus (BA 6/8/9)	0.001	2450	4.89	− 20	6	50
L inferior frontal gyrus (BA 47)	0.001	3297	5.68	− 34	28	− 6
L superior and inferior parietal cortex (BA 7/40)	0.001	2712	4.53	− 52	− 44	46
R superior and middle frontal gyrus (BA 6/8/9)	0.001	3528	4.83	44	34	28
R inferior frontal gyrus (BA 47)	0.005	384	4.10	32	20	4
R/L caudate nuclei, thalamic nuclei, brain stem	0.001	2092	4.29	16	0	16
Cerebellum	0.005	382	3.87	2	− 60	− 36
R superior and inferior parietal cortex (BA 7/40), middle and superior occipital gyrus (BA 19)	0.001	1932	4.19	42	− 52	44
(ii) Visual (WM–control)						
L superior frontal gyrus (BA 6)	0.001	1547	4.66	0	16	46
L inferior and middle frontal gyrus (BA 44/9)	0.001	3337	4.78	− 56	12	20
L inferior frontal gyrus (BA 47), caudate nucleus, thalamus	0.001	1354	5.48	− 30	24	− 10
R middle and inferior frontal gyrus (BA 9/44/46)	0.001	4072	4.15	38	52	24
R caudate nucleus, thalamic nuclei	0.001	783	4.06	18	− 4	18
L/R superior and inferior parietal cortex (BA 7/40), middle and superior occipital gyrus (BA 19)	0.001	6721	4.68	− 52	− 44	46
(iii) Auditory (WM–control) minus visual (WM–control)						
L middle frontal gyrus (BA 9), L inferior frontal gyrus (BA 44/45)	0.011	248	3.92	− 52	22	24
L middle frontal gyrus (BA 9/8/46), L superior frontal gyrus (BA 9/8)	*0.002*	*314*	*3.90*	*− 30*	*34*	*34*
L middle (BA 20/21/22) and superior (BA 22/48) and temporal gyrus	*0.004*	*278*	*3.43*	*− 52*	*6*	*− 14*
R middle (BA 20/21) and superior (BA 48) temporal gyrus	*0.018*	*231*	*3.71*	*44*	*− 24*	*− 2*
(iv) Visual (WM–control) minus auditory (WM–control)						
L intraparietal sulcus (BA 7), L inferior parietal gyrus (BA 7/40)	0.001	405	3.71	− 36	− 58	56
L lingual and fusiform gyrus (BA 19)	*0.006*	*266*	*3.28*	*− 24*	*− 56*	*− 4*
L inferior (BA 19/37) and middle occipital gyrus (BA 37), L fusiform gyrus (BA 19), L inferior temporal gyrus (BA 37)	*0.001*	*772*	*3.51*	*− 42*	*− 68*	*− 10*
L middle occipital gyrus (BA 18/19), L calcarine (BA 17/18), L lingual gyrus (BA 18/19)	*0.012*	*243*	*3.21*	*− 18*	*− 72*	*10*
R lingual gyrus (BA 17/18/19), R fusiform gyrus (BA 19/37), R inferior temporal gyrus (BA 20/37), R cerebellum 6	*0.001*	*1509*	*5.06*	*18*	*− 66*	*4*

Brain regions that show modality differences as a result of deactivation (greater activation in the control, compared to WM, tasks, see text for details and Fig. 3 for illustration) are shown in italics. In (iii), the right caudate–putamen activation cluster contains both activated and deactivated voxels. For each significant cluster, region of activation, significance level, number of activated voxels, maximum Z score and location of peak in Talairach coordinates are shown. Each cluster was significant after height and extent correction (P < 0.05).
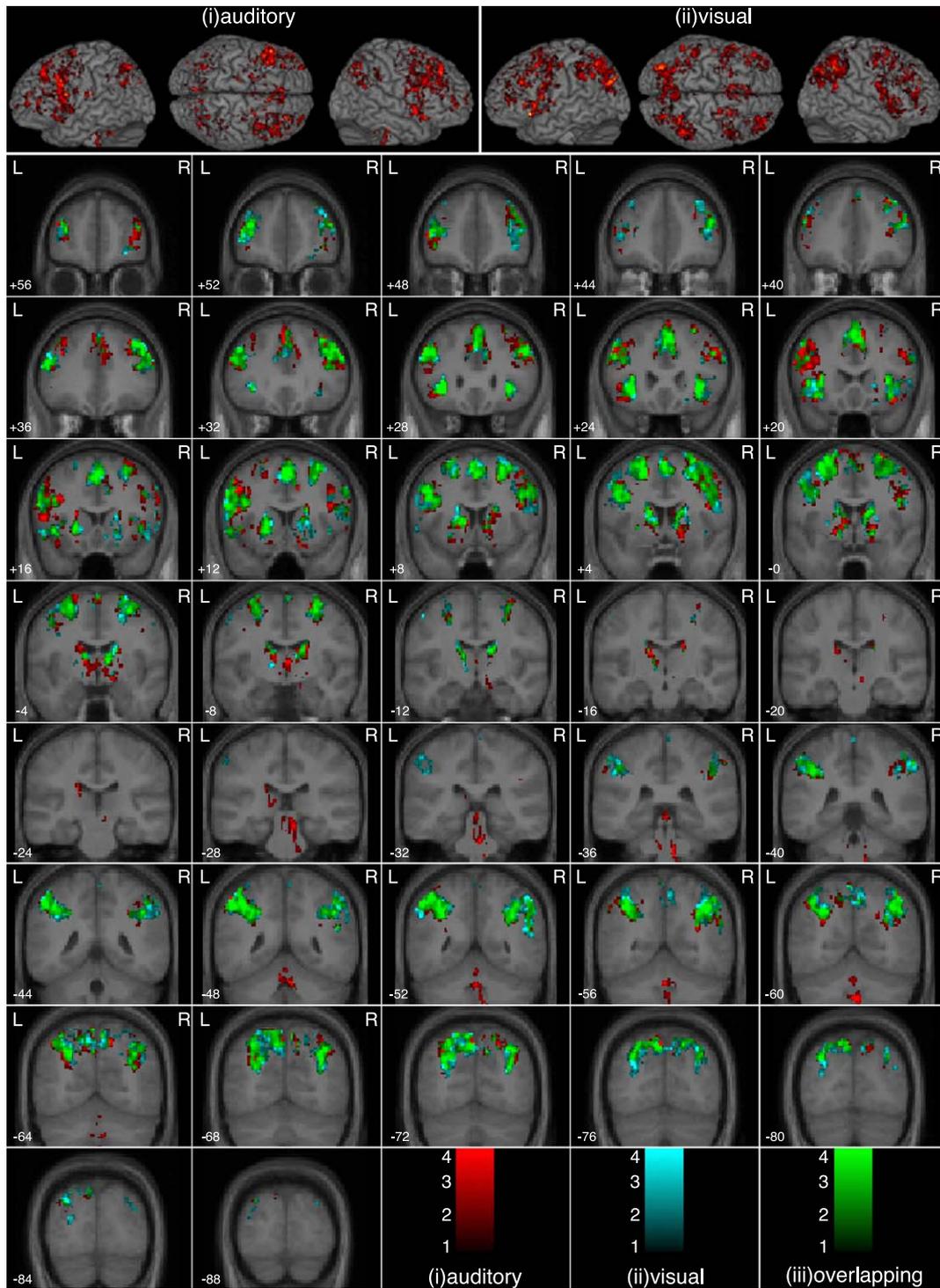
Fig. 1. Top: Surface rendering of brain areas that show significant activation during (i) auditory (left) and (ii) visual (right) WM. Bottom: Composite montages of brain areas that show significantly greater activation during (i) auditory WM only (red), (ii) visual WM only (blue), and (iii) both auditory and visual WM overlapping (green). Each cluster was significant after correction for multiple spatial comparisons ($P < 0.05$). Activations are shown superposed on group-averaged, spatially normalized, T1-weighted structural images.

Gaussian random fields as implemented in SPM99. This method takes advantage of multivariate regression analysis and corrects for temporal and spatial autocorrelations in the fMRI data (Friston et al., 1995). A within-subjects procedure was first used to model all the effects of interest for each subject; random effects analysis (Friston et al., 1999) was then used to determine significant ($P < 0.05$ height; $P < 0.05$ extent) clusters of activation corrected for multiple spatial comparisons (Poline et al., 1997) at the group level for each effect. Details of these analysis procedures have been described previously (Menon et
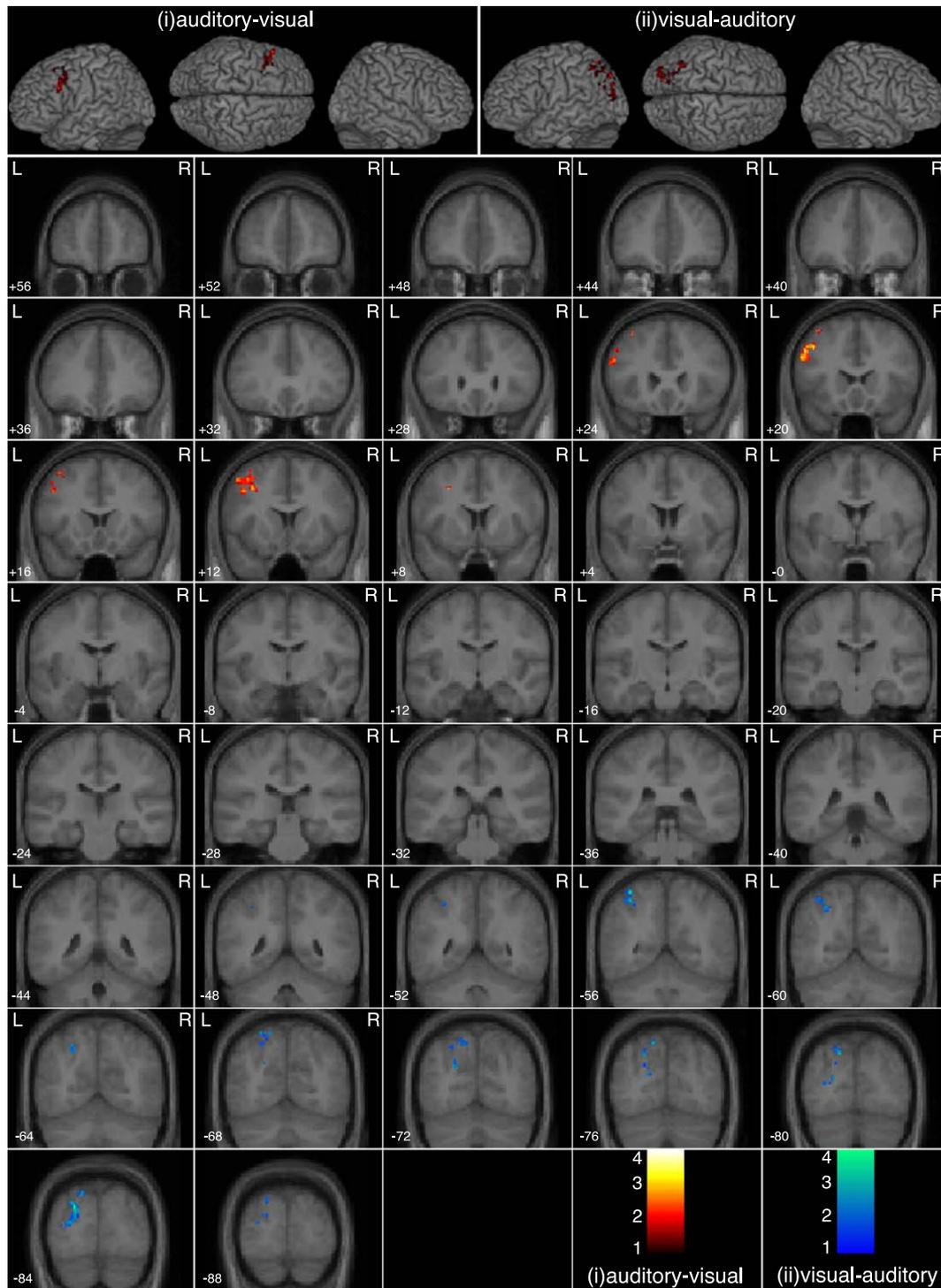
Fig. 2. Top: Surface rendering of brain areas that show significantly greater activation during (i) auditory, compared to, visual WM (left) and (ii) visual, compared to auditory WM (right). Bottom: Composite montages of brain areas that show significantly greater activation during (i) auditory, compared to visual, WM (red) and (ii) visual, compared to auditory, WM (blue). Each cluster was significant after correction for multiple spatial comparisons ($P < 0.05$). Activations are shown superposed on group-averaged, spatially normalized, T1-weighted structural images.

al., 2000). Activation foci were superimposed on high-resolution T1-weighted images and their locations interpreted using known neuroanatomical landmarks (Duvernoy et al., 1999; Mai et al., 1997). MNI coordinates were transformed to Talairach coordinates using a nonlinear transformation (Brett, 2000).

Effects of interest included the following within-modality comparisons: (1) aud-VWM (auditory VWM—auditory control) and (2) vis-VWM (visual VWM—visual control); and the following between-modality comparisons: (3) aud-VWM–vis-VWM (auditory VWM—auditory control) *minus* (visual VWM—visual

control) and (4) vis-VWM–aud-VWM (visual VWM—visual control) *minus* (auditory VWM—Auditory control). In the latter two comparisons (comparisons 3 and 4), which involve double subtractions, additional analyses were conducted to distinguish between differences arising from experimental task-related increases in activation, as opposed to control task-related decreases in activation (or "deactivation"). To examine clusters in comparison 3, the mean Z scores in these clusters were computed based on voxel-wise activation–deactivation in comparisons 1 and 2. Clusters in comparison 3 were categorized as arising from deactivation if this mean Z score was less than 0 in comparison 2. Similarly, to examine clusters in comparison 4, the mean Z scores in these clusters were computed based on voxel-wise activation–deactivation in comparisons 1 and 2. Clusters in comparison 4 were categorized as arising from deactivation if this mean Z score was less than 0 in comparison 1.

Results

Behavioral performance

Accuracy

Performance levels were high in both aud-VWM and vis-VWM experiments. In the aud-VWM experiment, accuracy in the VWM and control conditions was 95.44 ± 1.23% (mean ± SEM) and 97.62 ± 0.76%, respectively. In the vis-VWM experiment, accuracy in the VWM and control conditions was 94.44 ± 1.01% and 97.32 ± 0.72%, respectively. ANOVA of accuracy data revealed that the interaction between Modality (Auditory, Visual) and Task (VWM, control) was not statistically significant [$F(1, 13) = 0.33$; $P = 0.577$]. There was no difference in accuracy between modalities [$F(1,13) = 0.96$; $P = 0.341$]. Compared with the control conditions, accuracy was significantly lower in the VWM conditions ($F(1,13) = 6.27$; $P = 0.026$).

RT

In the aud-VWM experiment, RTs were 847.05 ± 24.05 ms in the VWM and 755.95 ± 24.57 ms in the control conditions. In the vis-VWM experiment, RTs were 676.09 ± 39.12 and 541.56 ± 22.01 ms, respectively. ANOVA of RTs revealed no interaction between Modality and Task [$F(1,13) = 2.36$; $P = 0.149$]; however, RTs were faster in the visual modality [$F(1,13) = 98.29$; $P = 0.001$]. RTs were significantly slower [$F(1,13) = 53.57$; $P = 0.001$] in the VWM, compared with the control conditions.

Brain activation

aud-VWM

Compared with the control condition (comparison 1 in Experimental procedure), we observed significant VWM-related activation bilaterally in the middle frontal gyrus (BA 9), superior frontal gyrus (BA 6), inferior frontal gyrus (BA 47), inferior parietal cortex (BA 40), superior parietal cortex (BA 7), middle and superior occipital gyrus (BA 19), caudate nucleus, thalamic nuclei and cerebellum (Table 1; Fig. 1).

vis-VWM

Compared with the control condition (comparison 2), significant WM-related activation was observed bilaterally in the middle frontal gyrus (BA 9), superior frontal gyrus (BA 6), inferior frontal gyrus (BA 44), inferior parietal cortex (BA 40), superior parietal cortex (BA 7), middle and superior occipital gyrus (BA 19), caudate nucleus and thalamic nuclei (Table 1; Fig. 1).

aud-VWM minus vis-VWM

A direct comparison of the auditory and visual WM tasks (comparison 3) revealed significant activation in the left middle (BA 8/9/46), superior (BA 9/8) and inferior (BA 44/45) frontal gyrus. Bilateral middle (BA 20/21/22) and superior (BA 22/48) temporal gyrus activations were also observed in this comparison (Table 1; Fig. 2). ROI analyses were conducted to determine if these activations arose from task-related increases during aud-VWM, or from task-related decreases ("deactivation") during vis-VWM. For each significant cluster, the mean Z scores were measured for activation in the aud-VWM (comparison 1) and vis-VWM (comparison 2) tasks. The data and analyses showed that left dorsolateral prefrontal cortex (DLPFC) activations are related to task-related increases during aud-VWM, rather than task-related decreases in vis-VWM (Fig. 3A). All other clusters arose from task-related decreases during vis-VWM, rather than task-related increases during aud-VWM.

vis-VWM minus aud-VWM

A direct comparison of the visual and auditory WM tasks (comparison 4) revealed significant activation in the left intraparietal sulcus (BA 7) and inferior parietal gyrus (BA 7/40). Bilateral activations were also observed in the lingual gyrus (BA 17/18/19), fusiform gyrus (BA 19/37) and inferior temporal gyrus (BA 20/37). Left inferior (BA 19/37) and middle (BA 18/19/37) occipital gyrus, left calcarine (BA 17/18) and right cerebellum (lobule VI) activations were also observed in this comparison (Table 1; Fig. 2). ROI analyses were conducted to determine if these activations arose from task-related increases during vis-VWM, or from task-related decreases ("deactivation") during aud-VWM. For each significant cluster, the mean Z scores were measured for activation in the aud-VWM (comparison 1) and vis-VWM (comparison 2) tasks. The data and analyses showed that left IPS activations are related to task-related increases during vis-VWM, rather than task-related decreases in aud-VWM (Fig. 3B). All other clusters arose from task-related decreases during aud-VWM, rather than task-related increases during vis-VWM.

To validate our findings of differential activation of left DLPFC (Talairach coordinates: − 52 22 24) and left IPS (− 36 − 58 56) during auditory and visual WM, statistical analysis (ANOVA) was computed on the mean Z scores in comparisons 1 and 2 for the left DLPFC and IPS clusters observed in comparisons 3 and 4, respectively (Fig. 3A, column 1 and Fig. 3B, column 1). This ANOVA revealed a significant interaction between Modality (Auditory, Visual) and Region (DLPFC, IPS) [$F(1,13) = 42.27$; $P = 0.00002$]. The left DLPFC showed greater activation during auditory, compared to visual, VWM ($P = 0.0003$) while the left IPS showed greater activation during visual, compared to auditory, VWM ($P = 0.0004$).

Discussion

The aim of our study was to examine similarities and differences in brain activation during auditory and visual verbal working

memory using quantitative comparison of activations during the two tasks. We observed a significant overlap of activation during aud-VWM and vis-VWM in several brain regions including the dorsolateral and ventrolateral prefrontal cortex, intraparietal sulcus, supramarginal gyrus and the basal ganglia, in both hemispheres (Table 1; Fig. 1). However, a direct statistical comparison of the two experiments showed important modality differences in the level of prefrontal and parietal cortex activation: the left IPS showed greater activation during vis-VWM, compared to aud-VWM processing, whereas the left DLPFC showed greater activation during aud-VWM processing. Although the DLPFC and IPS showed bilateral activation during both auditory and visual VWM, modality-specific differences were observed only in the left hemisphere, a finding consistent with left hemisphere bias for verbal information processing. The left DLPFC and left IPS activations reflect part of the frontoparietal loop that is known to play an important role in the encoding, storage and manipulation of VWM (Petrides et al., 1993a). As discussed below, our findings suggest important differences in the way internal representations of auditory and visual stimuli are generated, stored and used during VWM.

Performance

Performance levels were comparable in the two modalities, as has been reported in two previous studies that compared auditory and visual VWM (Ruchkin et al., 1997a; Schumacher et al., 1996). This is in contrast to immediate serial recall tasks, which generally show better performance with auditory as opposed to visual presentation: lists presented in the auditory modality are recalled better than those presented in the visual modality, the advantage being manifested in better recall of items towards the end of the list (Crowder, 1978). The *n*-back task used in our study differs fundamentally from serial recall tasks in that a rapid update of the contents of WM is required on a continuous basis. Furthermore, other studies have shown that a visual bias can be easily created with simple perturbations to the task: a visual advantage can be obtained with serial recall if participants are required to recall the list in two distinct sections using serial recall (Beaman, 2002). These observations suggest that representation of auditory and visual verbal material in short-term memory is context-dependent.

Our use of a within-subject design and a closely matched set of task conditions and stimuli ensured that task-related differences observed in our study arose primarily from modality-specific differences in VWM processing. Furthermore, because accuracy levels in both modalities were comparable for all subjects, differences in brain activations observed in our study cannot be attributed to differences in task difficulty. Although RTs were faster during vis-VWM, they were not differentially faster for the working memory, compared to the control, condition. In fact, RTs between modalities were somewhat larger for the control, compared to the working memory, condition, but not significantly so—the difference between RTs in the two modalities was 214 ms in the control condition and 171 ms in the WM condition. One possible reason for the longer RT in processing auditory stimuli is that, even though both auditory and visual stimuli were presented for a total of 500 ms, almost the entire auditory stimulus has to unfold in time before it can be reliably transduced and perceived; visual stimuli, on the other hand, can be transduced in its entirety the moment it is presented, thus accounting for the approximately 200-ms difference in RT between the two modalities. In view of these arguments, it is difficult to use RT information to assess relative timing of PFC and IPS activation in the two modalities. Therefore, where possible, we have chosen to examine our results in the context of convergent ERP findings by Ruchkin et al. (1997a).

Posterior parietal cortex

The greater activation observed during vis-VWM, compared to aud-VWM, in the left inferior parietal cortex was primarily restricted to the banks of the intraparietal sulcus (Table 1; Figs. 2 and 3). This area was activated during both visual as well as auditory VWM tasks; compared to aud-VWM, vis-VWM did not result in greater activation of any other region of the inferior parietal cortex. Lesion and imaging studies, mainly based on visual stimuli, have shown that the left IPS plays an important role in the phonological storage during VWM (Awh et al., 1996; Cohen, 1992; Fiez et al., 1996; Henson et al., 2000; Jonides et al., 1998; Paulesu et al., 1993; Shallice, 1988). Our data suggest that for both modalities, stimuli appear to be recoded and maintained by verbal rehearsal in a phonological short-term store in virtually similar regions. Such an interpretation is consistent with the Baddeley model of VWM (Baddeley, 1997, 2000), which has proposed that both visual verbal (i.e. nonspatial) and auditory verbal information are translated into a code that is stored and manipulated in the phonological loop (Baddeley, 1986), since it is subject to decay if unrehearsed. Further support for this interpretation comes from our finding that modality differences in activation were observed only in the left hemisphere. However, these modality differences observed in the left IPS in our study arise from quantitative, rather than qualitative, differences in activation. Although the phonological storage is accessed by both auditory and visual stimuli, one possibility suggested by our data is that auditory stimuli require less neuronal processing resources. This view would be consistent with the hypothesis that auditory stimuli have a more direct access to phonological representations (Baddeley, 1986; Penney, 1989).

It is important to note here that the differences observed in our study are not directly related to the way stimuli are encoded, since the appropriate control condition is subtracted out in the analysis of both aud-VWM and vis-VWM. Rather, the observed differences appear to arise from the manner in which the encoded stimuli are used for further VWM-related processing. In agreement with these observation, we did not observe any activation differences in earlier processing stages, such as the fusiform gyrus, where we might expect at least some transcoding to take place for visual stimuli (Allison et al., 1999; Mechelli et al., 2000). When compared to the baseline ("rest") state, the control task activates left fusiform and lingual gyrus regions where lexical codes are presumably represented. How this lexical representation is transformed into a phonological representation is largely unknown. In this comparison, we did not detect activation in the left IPS region during the control task, a finding consistent with other published studies. Henson et al. (2000) have suggested a key role for this region in phonological recoding, when such a recoding is necessary, as is the case with our 2-back working memory task, but not our control task. Thus, the greater activation of the left IPS during vis-VWM is possibly the result of additional processing involving access to parietal storage mechanisms. Such a view would be consistent with our finding
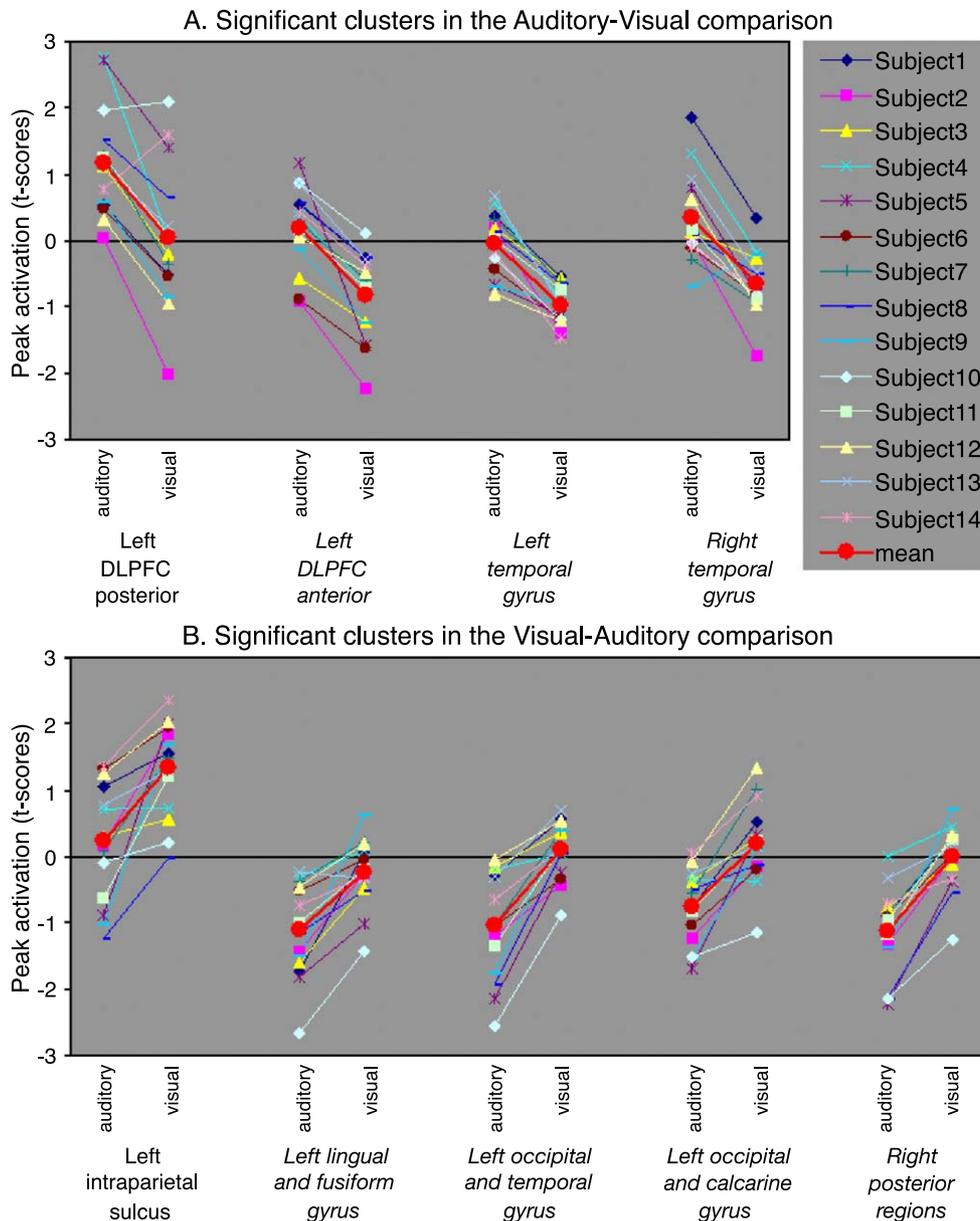
Fig. 3. Activation and deactivation in each cluster that showed greater activation during (A) auditory, compared to visual, WM and (B) visual, compared to auditory, WM. Activation, as measured by average t scores in each cluster is shown for each subject, along with the group mean (solid red line), for the auditory and visual tasks, compared to their respective control conditions. Clusters noted in italics arise mainly from deactivation in the visual and auditory tasks, respectively. The graphs clearly show that for the auditory, compared to visual, WM, task-related increased were observed only in the left DLPFC and that for the visual, compared to auditory, WM, task-related increased were observed only in the left IPS. Note that only the means of the DLPFC and IPS regions do not show negative peaks, all other modality differences shown in Table 1 arise from deactivation. DLPFC: dorsolateral prefrontal cortex.

that parietal lobe activation shows extensive overlap in activation in the two modalities. Alternatively, it is also possible that these differences may arise from fundamental differences in the neural representations of auditory and visual stimuli in phonological storage; however, fMRI has poor spatial and temporal resolution to resolve this issue. There is now very little evidence from neurophysiological studies to distinguish between these alternatives; however, a more parsimonious view of neuronal coding would suggest that a modality invariant representation might be maintained in phonological storage. Further research is needed to resolve whether the observed modality differences arise from differences in recoding, storage or both.

The poor temporal resolution of fMRI precludes precise determination of the temporal course of these events. However, comparisons with a related ERP study provide useful information when considered in conjunction with our study. Our findings are in excellent agreement with human electrophysiological study by Ruchkin et al. (1997a), which showed that presentation of visual stimuli resulted in an earlier and more persistent positive slow wave over centroparietal electrodes than did auditory stimuli during a VWM task. The onset of this slow wave is observed soon after stimulus presentation and extends about 2000–2500 ms beyond the termination of the stimulus, leading Ruchkin et al. to speculate that this ERP component could reflect the involvement of
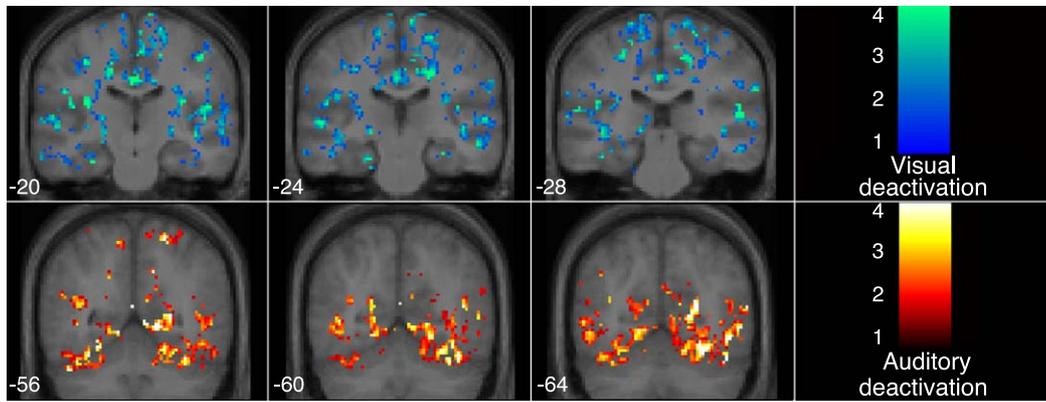
Fig. 4. Top: The superior and middle temporal gyri showed significant "deactivation" during visual WM, that is, greater activation during the control compared to the WM condition. Bottom: The lingual, fusiform and inferior temporal gyri showed significant "deactivation" during auditory WM. Other details as in Fig. 1.

a visual verbal store. Other related memory studies have also reported greater centroparietal ERPs during processing of visual verbal materials compared to processing of visuospatial information (Mecklinger and Pfeifer, 1996; Ruchkin et al., 1994, 1997b). However, the low spatial resolution of scalp-recorded ERPs precludes determination of the precise source of this positive deflection (Menon et al., 1997). Taken together, these data suggest that the parietal cortex is activated over a more prolonged period, perhaps reflecting additional recoding steps necessary for transformation and maintenance of a phonological code.

Dorsolateral prefrontal cortex

In addition to the left IPS, we also observed differences in the left DLPFC. However, in contrast to the IPS, greater activation in the DLPFC was observed during the aud-VWM, compared to the vis-VWM, task. Here again, similar regions of the DLPFC were activated bilaterally during both the vis- and aud-VWM tasks, suggesting that the differences are primarily quantitative. To date, the only human neuroimaging study that directly compared auditory and visual VWM did not find any differences in the frontal cortex (Schumacher et al., 1996). Our results, however, are consistent with the ERP study of Ruchkin et al. (1997a), who reported a larger frontal negative component for auditory, compared to visual, VWM. Furthermore, during aud-VWM, the onset of this frontal ERP component was 500–1000 ms earlier than during vis-VWM. The amplitude of the frontal auditory ERP component is greater throughout the delay interval, extending well into the response interval. Since the fMRI blood oxygenation level dependent (BOLD) signal reflects integration of neural response over several seconds, such an early and prolonged frontal ERP signal difference may underlie increased DLPFC activation during aud-VWM. Thus, our results provide new and more precise information about the location of prefrontal cortex generators of the frontal negativity observed in the Ruchkin et al. ERP study. More importantly, these findings may underlie behavioral observations that the memory representations of auditory stimuli may be more enduring (Beaman, 2002; Broadbent et al., 1980; Penney, 1989).

Extensive electrophysiological, lesion, and neuroimaging studies have established that the DLPFC plays a critical role in visual WM (Braver et al., 1997; Funahashi et al., 1989, 1991; Fuster, 1997; Fuster and Alexander, 1971; Goldman-Rakic, 1987; Owen,

1997; Owen et al., 1996, 1998; Petrides et al., 1993a,b; Rowe et al., 2000). However, the precise role played by the DLPFC in maintenance of items in VWM versus selection of response actions has been controversial. Animal studies have shown that cells in the DLPFC fire continually during the delay period, suggesting that one role of the DLPFC is the active maintenance of information (Goldman-Rakic, 1987). Human studies have also related activation in the DLPFC to WM maintenance, but it is increasingly clear that the DLPFC has a more critical role in control and monitoring processes during WM (Braver et al., 1997; Funahashi et al., 1989, 1991; Owen, 1997; Owen et al., 1996, 1998; Petrides et al., 1993a; Rowe et al., 2000) in comparison to other regions such as the ventrolateral prefrontal cortex (VLPFC) and the parietal cortex. Because animal studies have used only visuospatial stimuli, little information is available about differences in the neural mechanisms involved in auditory and visual VWM processing. However, based on the time course of the frontal ERP components observed by Ruchkin et al. (1997a), and their dependence on memory load, we suggest that modality differences observed in the DLPFC reflects a more prolonged control and monitoring processes in the auditory WM condition.

Premotor and ventrolateral prefrontal cortex

Interestingly, no differences were observed in the VLPFC. Researchers have argued that the VLPFC plays an important role in WM, although its precise role in the organization of information, interference resolution and selective retrieval, versus maintenance and manipulation of information in WM is still being debated (Fletcher and Henson, 2001; Owen, 2000). No modality differences were found in the premotor cortex (PMC) or the supplementary motor area (SMA), suggesting that operations related to motor preparation and transformation of motor plans into action are similar in both modalities. Moreover, no differences were found in Broca's area, part of the prefrontal cortex involved in subvocal rehearsal process (see Smith and Jonides, 1998, for a review). Although Broca's area, the PMC and the VLPFC have all been implicated in phonological rehearsal, these regions are primarily involved in the articulatory maintenance of phonological information (Gruber and von Cramon, 2001; Henson et al., 2000). It has been suggested that phonological information can nevertheless be maintained in parallel by a frontoparietal loop involving only the DLPFC and the inferior parietal lobule, even under conditions of

articulatory suppression (Gruber and von Cramon, 2001). Thus, the regions that show significant differences between modalities in our study are precisely those prefrontal regions where the most robust representations can be maintained. Furthermore, our data suggest that the verbal rehearsal processes are substantially similar in both modalities.

Comparisons with other related studies

Klingberg (1998) examined regional cerebral blood flow (rCBF) during performance of an auditory working memory (WM) task, a visual WM task, both WM tasks (dual task) and a control condition with nonverbal stimuli—auditory tones and visual intensity levels. Compared to the control condition, the auditory and visual WM tasks activated sensory-specific areas in the superior temporal gyrus and occipital pole, respectively. However, both WM tasks activated overlapping parts of cortex in the dorsolateral prefrontal, inferior parietal and cingulate cortex. No direct statistical comparison was made between activation in the auditory and visual WM tasks, perhaps because of the few subjects ($N = 6$) used in the study. Dade et al. (2001) found that both olfactory and face working memory engaged dorsolateral and ventrolateral frontal cortex when the task requirements were matched. Similarities and differences in activity were noted in parietal lobe regions, with both tasks engaging the inferior parietal cortex, but the visual working memory task showed greater activity within the left superior parietal cortex. Our study found modality differences in the PPC, but these differences were quantitative, rather than qualitative. Nevertheless, both studies point to increased involvement of the PPC in visual working memory compared to other modalities, auditory in our case and olfactory in the case of the Dade et al. study.

Several recent fMRI studies have addressed the issue of auditory versus visual processing, albeit not in the context of working memory. Most of these studies have dealt with processing of words: for example, the priming study by Buckner et al. (2000); word processing by Chee et al. (1999); and word comprehension by Booth et al. (2002). Buckner et al. (2000) found evidence for repetition priming in the left inferior frontal gyrus and the left inferior temporal cortex to both visual or auditory cues, suggesting that these regions may be modulated in a top-down fashion during repetition priming, independent of (or in parallel with) stimulus-driven perceptual processes. Chee et al. (1999) examined brain activations associated with semantic processing of visual and auditory words. They observed that visual and auditory semantic tasks both activated the left inferior frontal (BA 45), bilateral anterior prefrontal (BA 10, 46), left premotor regions (BA 6) and anterior SMA (BA 6, 8). Left posterior middle temporal and fusiform gyrus activations were observed only during the auditory semantic task but they were not above threshold during visual word presentation. Booth et al. (2002) observed modality-independent activation during semantic processing in the heteromodal cortices of the left inferior frontal gyrus (BA 46, 47) and left middle temporal gyrus (BA 21), with modality-specific activations confined to unimodal association cortex—the fusiform gyrus (BA 37) for written words and the superior temporal gyrus (BA 22) for spoken words. Several studies have examined modality differences in oddball tasks and reported a high degree of spatial overlap in frontal and parietal areas (Stevens et al., 2000). Interestingly, none of these studies have conducted a direct statistical comparison between effects in the two modalities, so that amodal effects, if any, were never rigorously examined. Besides, most of these studies used a fixed effects model analyses on a limited number of subjects, typically 6–7, thus restricting the interpretation to the subjects studied. In this regard, our study, which has several methodological advances, points to the importance of quantitative comparisons as opposed to comparisons based on visual inspection, which can often be quite misleading.

Reciprocal deactivation in auditory and visual cortices

Apart from the left DLPFC and the left IPS, other brain areas were also differentially involved in visual and auditory working memory (Table 1). To examine the question of which differences arose from task-related increases in activation and which ones arise from deactivation in the double subtraction, the level of activation and deactivation in each of the two experiments was computed on a subject-by-subject basis (Fig. 3). By deactivation, we mean here the areas that showed greater activation in the control, compared to, WM tasks. These analyses strengthen and confirm our findings as only differences in the DLPFC and IPC were related to WM task-related increases in activation (Fig. 3). Other modality differences listed in Table 1 arose clearly from task-related decreases in activation or "deactivation" as shown in Fig. 3. Specifically, we detected decreases bilaterally in the superior and middle temporal (auditory) cortex during vis-VWM and in the occipital (visual) cortex during aud-VWM (Fig. 4). Furthermore, we also observed convergence of deactivation with activation in the control conditions. For example, the deactivated left superior temporal cortex regions during visual VWM also showed activation during the auditory control condition, when compared to "rest". These findings are consistent with the study of Laurienti et al. (2002), which revealed that ongoing activity in the visual cortex could be reduced during processing of simple auditory stimuli, and similarly activity in the auditory cortex could be reduced during processing of simple visual stimuli. Such cross-modal inhibitory processes may help provide preferential access to heteromodal cortex. Alternatively, these processes may also increase the relative salience of specific sensory events. Further research is warranted to examine these possibilities.

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