

## Neural correlates of dual-task performance after minimizing task-preparation

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Previous dual-task neuroimaging studies have not discriminated between brain regions involved in preparing to make more than one response from those involved in the management and execution of two tasks. To isolate the effects of dual-task processing while minimizing effects related to task-preparatory processes, we employed a blocked event-related design in which single trials and dual trials were randomly and unpredictably intermixed for one block (mixed block) and presented in isolation of one another during other blocks (pure blocks). Any differences between dual-task and single-task trials within the mixed block would be related to dual-task performance while minimizing any effects related to preparatory differences between the conditions. For this comparison, we found dual-task-related activation throughout inferior prefrontal, temporal, extrastriate, and parietal cortices and the basal ganglia. In addition, when comparing the single task within the mixed block with the single task presented in the pure block of trials, the regions involved in processes important in the mixed block yet unrelated to dual-task operations could be specified. In this comparison, we report a pattern of activation in right inferior prefrontal and superior parietal cortices. Our results argue that a variety of neural regions remain active during dual-task performance even after minimizing task-preparatory processes, but some regions implicated in dual-task performance in previous studies may have been due to task-preparation processes. Furthermore, our results suggest that dual-task operations activate the same brain areas as the single tasks, but to a greater magnitude than the single tasks. These results are discussed in relation to current conceptions of the neural correlates of dual-task performance.

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### Introduction

Performing two tasks concurrently is commonly considered one of the hallmark examples of a cognitive process or set of processes that requires executive functioning. Specifically, dual-task processing requires the allocation of top-down (i.e. central executive) attentional control for the coordination and management of multiple tasks in working memory (Baddeley, 1986). Recently, neuroimaging studies have examined the neural substrates of dual-task processing and have reported a pattern of prefrontal, parietal, temporal, and subcortical activation associated with concurrently performing two tasks (Adcock et al., 2000; Bunge et al., 2000; D'Esposito et al., 1995; Herath et al., 2001; Jiang, 2004; Schubert and Szameitat, 2003). However, despite these important contributions to understanding the neural substrates of dual-task processing, a number of important questions remain unanswered.

Previous neuroimaging studies using dual-task or psychological refractory period (PRP) paradigms have typically employed block designs (e.g. Adcock et al., 2000). One inherent limitation of block designs is that only one trial type is typically presented per block. This allows participants to predict and prepare for the particular task presented during that block. Therefore, comparing the brain activation from two different blocks of trials may result in some activation unrelated to the cognitive process being investigated, such as greater levels of task-preparation. For example, in blocked dual-task studies, dual-task blocks require greater executive and attentional control, enhanced motor and attentional preparation, greater working memory demands, and greater cognitive flexibility than single-task blocks. Motivation may also differ between blocks. Therefore, a comparison of dual-task and single-task blocks may show activation associated with differences due to any number of cognitive processes. Although many different cognitive processes are probably important for successful dual-task performance, some of them may be unnecessary for the coordination and sequencing of multiple tasks. For example, numerous behavioral studies have suggested that at least a proportion of the processing associated with dual-task performance reflects a

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limitation in the ability to keep two or more tasks prepared at the same time, even though the effects of preparation are not limited to dual-task conditions (Gottsdanker and Shragg, 1985; Koch et al., 2004; Pashler, 1984, 1994; Pashler and Johnston, 1998).

Other neuroimaging studies have employed block designs in which the blocks varied by the interval separating the tasks rather than the number of tasks performed. For example, some studies have compared neural activation during a block of trials in which the stimulus-onset asynchrony (SOA) between the first and second stimulus is very short to a block of trials in which the SOA between the first and second stimulus is longer (Herath et al., 2001; Jiang et al., 2004; Jiang, 2004; Schubert and Szamietat, 2003; Szameitat et al., 2002). The benefit of employing this type of design is that it compares activation from two types of dual-task blocks (e.g. dual-task with short SOA versus dual-task with long SOA) and circumvents some of the problems when trying to directly compare dual-task blocks to single-task blocks. However, findings from SOA manipulations in block designs could produce results that are related to forcing participants to prepare two tasks with a short SOA in one block but allowing participants to prepare for each task one at a time in blocks with long SOAs (Dreher and Grafman, 2003). Therefore, similar to dual/single-task blocked studies, preparation-related activation (as well as other factors) could have contributed to previous results that have employed SOA manipulations.

In support of this argument, studies of task-preparation have frequently reported a pattern of activation in brain regions similar to those reported in dual-task and PRP studies, including the right inferior frontal gyrus (Brass and von Cramon, 2004; Dreher et al., 2002; Sohn et al., 2000), left inferior frontal junction (Brass and von Cramon, 2002, 2004), and left inferior frontal gyrus (Perianez et al., 2004), thus lending credence to the possibility that some of the dual-task-related activation in previous studies was actually associated with greater engagement of preparatory processes rather than being involved in processes necessary for dual-task performance. The current study was designed to elucidate the regions important in dual-task processing when the degree of task-preparation between single and dual tasks was minimized.

One common method to examine and minimize preparatory effects is to include a block of trials in which single-task trials are randomly and unpredictably intermixed with dual-task trials. It is thought that this type of mixed task design requires participants to always be prepared to respond to two tasks regardless of whether the task at hand is a single-task or a dual-task (Pashler, 1994, 1998). Therefore, a comparison of dual-task trials in a mixed block (DM) with single-task trials in a mixed block (SM) provides a measure of dual-task processing in which the level of preparation and working memory demands are equivalent between the two conditions. Furthermore, a comparison of the reaction time and accuracy from the single-task trials in a mixed block (SM) of dual- and single-task trials with the reaction time and accuracy of single-task trials presented in a block composed purely of single-task trials (SP) is thought to provide a measure of the slowing associated with preparatory processes (Pashler and Johnston, 1998). If the comparison between the SM task and the SP task reveals activation in areas that have been reported in previous dual-task and PRP studies, such as the inferior frontal gyrus, it would argue that these regions are not limited to dual-task processes (e.g. management of multiple concurrent tasks).

However, task-switching processes (i.e. the need to switch between two different single tasks in mixed blocks as compared to the repeated performance of a single task in pure single-task blocks) are inherent within a mixed block of dual and single trials and are not present within single-task blocks of trials. Therefore, one could argue that the activation resulting from a comparison of SM and SP trials could be due to the need for task-switching processes in the mixed block instead of differential preparation. In order to investigate this possibility, we analyzed the activation associated with a switch between one type of single-task and another type of single-task within the mixed block and compared the resulting activation to the results from a repetition of a single-task within the mixed block. This analysis will reveal which areas of activation from the SM versus SP comparison are due to task-switching processes.

We predicted that the comparison of DM versus SM conditions would reveal regions that were essential in managing and coordinating the selection and execution of multiple concurrent tasks. These regions included the parietal and prefrontal regions, which have both been implicated in similar executive (Brass and von Cramon, 2002; MacDonald et al., 2000), attentional control (Banich et al., 2000), and response selection (Milham et al., 2001) processes in other tasks. In addition, we predicted greater anterior cingulate cortex activity for the DM condition due to increased response conflict and heightened potential for error (Botvinick et al., 1999) as well as other potential roles in modulating attentional control (Weissman et al., 2003) for the DM condition. Furthermore, clinical (Brown and Marsden, 1991), split-brain (Pashler et al., 1994), and prior neuroimaging (Adcock et al., 2000) investigations report a role of subcortical structures in dual-task processing, therefore we predicted that subcortical regions such as basal ganglia and thalamus would also be found for this comparison.

In the comparison of the SM versus SP comparison, we predicted that regions uninvolved in dual-task processing would be established. Specifically, if the SM condition involved a greater degree of task-preparatory processes than the SP condition, then we should observe greater SM activity in regions commonly implicated in preparatory processes including superior parietal cortex (Corbetta et al., 2000; Corbetta and Shulman, 2002; Shulman et al., 1999), right prefrontal cortex (Brass and von Cramon, 2004; Dreher et al., 2002; Sohn et al., 2000), and premotor cortex (Adam et al., 2003; Matsumoto et al., 2003). However, if any regions from this analysis overlap with the task-switching results, then task-switching processes would provide an alternative explanation for these effects.

In the current experiment, we examined the regions involved in dual-task processes in an event-related paradigm in which we could minimize effects related to preparation. We also assessed whether any of the inferior prefrontal regions that have recently been implicated in dual-task processing could be accounted for by task-preparation. Finally, we examined whether task-switching processes could account for differences in activation between the mixed block of single trials and pure block of single trials.

## Method

### *Participants*

Thirty-three volunteers (20 female) from the University of Illinois student community between the ages of 19 and 32

participated (mean age = 23.66). All participants were right-handed native English speakers and were excluded from the study if they reported claustrophobia, metallic implants, or previous head trauma. The University of Illinois Institutional Review Board approved the study, and all volunteers signed an informed consent and were paid \$15 per hour for participating.

### Stimuli and task

#### Single-pure task 1: color discrimination

A fixation cross was displayed on the screen at all times in which stimuli were absent. The letter 'X' was printed in either the color yellow or the color green against a black background directly above the point of fixation. Participants were asked to respond, via a button press on a four-button response pad, to the color of the letter 'X', one button if yellow, another button if green. In the same position as the stimuli in the single-pure task 2 (see below), a star (\*) was displayed that acted to equate the total number of visual stimuli on the screen for both dual-tasks and single-tasks (see Fig. 1). This allowed for a comparison of visual cortex activation between single and dual tasks. The color sequence was first-order counterbalanced, and participants were asked to respond as quickly and accurately as possible.

#### Single-pure task 2: letter discrimination

Similar to the color discrimination task, a fixation cross was displayed on the screen at all times when stimuli were absent. The letter 'B' or the letter 'C' was printed on the screen in white against a black background directly beneath the fixation cross (see Fig. 1). Participants were asked to respond, via a button press on a four-button response pad, to the letter, one button if the letter was 'B', another button if the letter was 'C'. A star (\*) was displayed in the same location as the stimuli in the color discrimination task that acted to equate the total number of visual stimuli on the screen for both dual-tasks and single-tasks. The letter sequence was first-

order counterbalanced, and participants were asked to respond as quickly and accurately as possible.

#### Dual-pure task

A fixation cross was displayed on the screen at all times whenever stimuli were absent. The stimuli from both single tasks were presented simultaneously on the screen (0 ms SOA). The stimuli from the color discrimination condition were always presented above fixation, and the stimuli from the letter discrimination condition were always presented below fixation. Parameters from each of the stimuli remained the same from each of the single tasks. Participants were instructed to respond as quickly and accurately as possible and not to withhold any responses. Participants were not instructed to respond to the stimuli in a particular sequence, but most participants responded to the color discrimination task first followed by the letter discrimination task.

Although the dual-pure condition was included in the methods of the experiment, the results from this condition were not directly relevant to the questions being addressed and therefore will not be analyzed and reported in the present paper.

#### Mixed block

Similar to previous conditions, a fixation cross was displayed in the center of the screen at all times whenever stimuli were absent. This condition employed a pseudo-random presentation of both dual-task trials and single-task trials in which the sequence of the trial order was unpredictable (see Fig. 1). Making the trial sequence unpredictable was important for our hypotheses because task-preparation and the brain regions associated with task-preparation are modulated by the timing and predictability of the sequence (Sohn et al., 2000; Dreher et al., 2002). Therefore, in order to reduce effects related to task-preparation, it was essential for us to use an unpredictable sequence in the mixed block. In addition, the sequence of the stimuli was first order counterbalanced.

Because some of the activation for the single condition in the mixed block could be due to task-switching between two different types of single tasks, we decided to assess the effects of non-switch single-task trials (NSW) versus switch single-task trials (SW) within the mixed block. NSW trials were defined as a repetition of one type of single trial within the mixed block such that trial  $n$  and trial  $n + 1$  were both color discrimination or letter discrimination tasks. SW trials were defined as a change from one trial type to another such that trial  $n$  and trial  $n + 1$  consisted of both a color discrimination and a letter discrimination trial.

#### Procedure

The stimuli were presented via an MR compatible fiber optic goggle system (Magnetic Resonance Technologies), and responses were collected via a four-button response pad. Near visual acuity was corrected to 20/30 with lenses that fit into the goggles. The stimulus onsets were fixed at an interval of 4.5 s, and each stimulus remained on the screen for 2 s, which left an interstimulus baseline of 2.5 s. In addition, we included an 18-s break after every 8th trial in order to ensure a longer baseline to compare task activation. Each SM block had a total of 40 trials, while each mixed block had 60 SM trials and 60 DM trials for a total of 120 trials per mixed block. Within the mixed block of trials, there were approximately 15 SW trials and 15 NSW trials for a total of about 30 SW trials and 30 NSW trials for the entire experiment. Although the trial order was pseudo-random and changed across participants, the

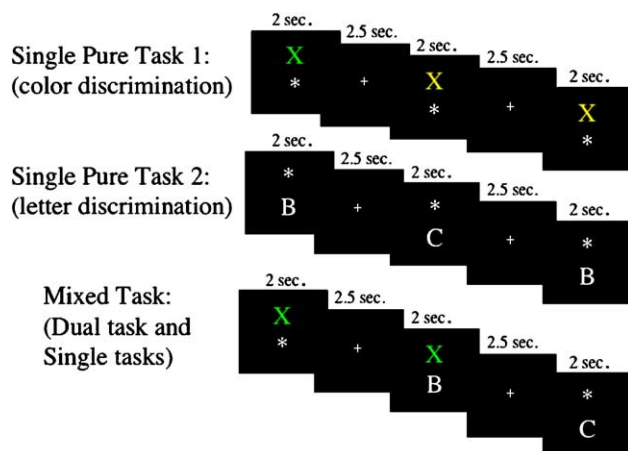


Fig. 1. A graphic illustration of the tasks. Each stimulus was presented for a duration of 2 s with an ISI of 4.5 s. In the color discrimination task, participants were instructed to respond to the color of 'X' by pressing one of two buttons. In the letter discrimination task, participants were instructed to respond to the identity of the letter 'B' or 'C' by pressing one of two buttons. The two tasks were performed on different hands using different buttons. In the mixed task, the participants were instructed to respond to both types of tasks (the letter and/or color discrimination tasks) as quickly as possible without withholding any responses.

block order was fixed for everyone. Specifically, the participants began with a block of color discrimination trials followed by a block of letter discrimination trials, a block of dual-pure trials, and then by a mixed block of dual and single trials. These four blocks were then repeated in the opposite order (mixed block, dual-pure task, letter discrimination, color discrimination). This type of presentation controls for temporal confounds including habituation and practice effects, while allowing the single tasks to always be performed before the dual tasks. In between each block of trials was a short break period (~30 s) in which the participant was able to rest. The button mapping for each stimulus condition was counterbalanced across participants. Similar types of hybrid paradigms have been used previously to investigate the effects of task-switching (Braver et al., 2003) and Stroop tasks (Milham et al., 2001) on brain function.

#### *MR parameters and preprocessing*

Imaging was performed with a 3 T head-only Siemens Allegra MRI scanner. For the functional MRI (fMRI) protocol, we employed a fast echo-planar imaging (EPI) sequence with blood oxygenation level dependent (BOLD) contrast and collected a total of 1760 T2\* weighted images per participant (TR = 1.5; TE = 26; flip angle = 60). Sixteen slices (5 mm thickness; 3.75 mm in plane resolution; 0 gap) were collected in an ascending interleaved fashion parallel to the anterior and posterior commissures.

Two sets of anatomical images were also collected during the scanning session: a high-resolution T1-weighted MPRAGE (0.96 mm × 0.96 mm × 1.3 mm) and a lower resolution T1-weighted image collected in the same plane as the EPI data. Both sets of anatomical images were skull-stripped using a brain extraction technique (Smith, 2002) and subsequently used for registration purposes.

After reconstruction, the first 6 images were removed in order to allow the magnet to reach steady state. The data were pre-processed using FSL version 3.1 (<http://www.fmrib.ox.ac.uk/fsl/>). Images were slice-time corrected, motion-corrected using a rigid body algorithm in MCFLIRT, brain extracted using a robust deformable algorithm (Smith, 2002), temporally filtered with a Gaussian high pass cut-off of 50 s and a low pass cut-off of 1.5 s, and spatially smoothed with a 7 mm full-width half-max 3D Gaussian kernel.

#### *Data analysis*

The behavioral data (response time and accuracy) were analyzed with one-way ANOVAs. Each ANOVA had three levels (single-pure, single-mixed, dual-mixed). In addition, the task-switching analyses were analyzed by a one-way ANOVA with three levels (single-pure, non-switch, switch). All behavioral data were analyzed using SPSS 11.02 for Mac.

The neuroimaging data were convolved using a double-gamma function with temporal derivatives in an event-related analysis. We first calculated the mean activation above baseline for each block and each condition while using the six motion correction vectors and error trials as covariates. Errors were coded in the dual-task trials when participants incorrectly responded to one or both of the items on any given trial. Next, we averaged the activation corresponding to the same condition from the different blocks and calculated the contrasts and direct comparisons of interest within subject. A single parameter estimate for each variable and

each contrast for every participant resulted from this first level analysis. These parameter estimates and variance maps for each participant were then forwarded to a higher-level group analysis in which a mixed-effects ANOVA was carried out to assess the regions for both the main effects of interest and direct comparisons between conditions.

Registration was carried out on the first-level analysis for each subject by registering a mean functional image for each participant to his or her skull-stripped low-resolution in plane anatomical. The in plane anatomical was then registered to a skull-stripped high-resolution anatomical image, which was then registered to a skull-stripped standard template image (MNI space). Transformation matrices from each of these registration steps were then applied to the parameter estimates. All MNI space coordinates were transformed to Talairach space after the group analysis was complete.

We focused on the effects of a few direct comparisons that tested the hypotheses of interest for this study. First, the direct comparison between DM and SM trials isolated the activation due to dual-task performance while minimizing the effects related to preparation. Second, the direct comparison between SM and SP trials isolated the activation associated with processes not specific to dual-task performance within the mixed block of trials. Third, the direct comparison between SW and NSW trials within the mixed blocks assessed the effects related to task-switching which were examined for overlap with the brain regions active in the SM versus SP comparison.

Analysis was carried out using FEAT (FMRI Expert Analysis Tool) Version 5.1, part of FSL (FMRI's Software Library, <http://www.fmrib.ox.ac.uk/fsl/>). Higher-level analyses were carried out using FLAME stage 1 only (i.e. without the final MCMC-based stage) (Behrens et al., 2003). All *Z* statistic images were thresholded using clusters determined by  $Z > 3.1$  and a (corrected) cluster significance threshold of  $P = 0.01$  (Worsley et al., 1992; Friston et al., 1994; Forman et al., 1995). All images were rendered in Mri3DX version 5.

## **Results**

The questions posed in the current study required the comparison of only a few of the conditions. Therefore, for the behavioral and neuroimaging analyses, we focused only on the conditions and comparisons that were of direct interest for our hypotheses. These included the DM versus SM, SM versus SP, and SW versus NSW comparisons. Other comparisons including those involving the DP condition will be discussed elsewhere.

Furthermore, in order to determine the brain areas that overlapped for all conditions, we performed a conjunction analysis between all three conditions of interest. For the sake of brevity, we will only report the areas of common activation (conjunction analysis) and the results from the direct comparisons between the conditions of interest.

#### *Behavioral data*

##### *Reaction time*

We analyzed the reaction time (RT) data using a one-factor ANOVA with three levels (single-pure, single-mixed, dual-mixed; we used the response time from the first response from the dual-task). The mean reaction time and standard deviations for each condition are described in Table 1. We found a significant main

Table 1

The top three rows show the mean reaction times, accuracy, and standard deviations (in parentheses) for all three conditions

Condition	Reaction times	Accuracy
Single-pure	724.66 (144.88)	0.967 (0.025)
Single-mixed	1072.99 (156.19)	0.935 (0.035)
Dual-mixed	1328.98 (182.18)	0.898 (0.052)
Single-mixed non-switch	1059.75 (105.86)	0.938 (0.037)
Single-mixed switch	1085.76 (98.00)	0.931 (0.032)

The bottom two rows show the means and standard deviations for the response times and accuracy of the non-switch and switch trials from the single-mixed blocks.

effect of RT ( $F(2,31) = 115.92$ ;  $P < 0.001$ ). In addition, post-hoc analyses revealed that the RTs for all three levels were significantly different from one another (all comparisons at  $P < 0.001$ ). Importantly, participants were slower to respond to the DM condition than the SM condition and slower to respond to the SM condition than the SP condition (see Table 1).

We examined task-switching effects by using a one-factor ANOVA with three levels (single-pure, single-mixed non-switch, single-mixed switch). The mean reaction times and standard deviations for each condition are described in Table 1. We found a significant effect of RT ( $F(2, 32) = 96.05$ ;  $P < 0.001$ ). Post-hoc comparisons revealed a significant difference between SP and NSW tasks ( $P < 0.001$ ) and between SP and SW tasks ( $P < 0.001$ ) such that the RTs from the SW and NSW conditions were reliably slower than the SP condition. There was no difference between the NSW and SW conditions ( $P < 0.373$ ).

#### Accuracy

Similar to the RT data, we analyzed the accuracy (ACC) data using a one-way ANOVA with three levels (single-pure, single-mixed, dual-mixed; errors in the dual-task were calculated if participants responded incorrectly to either stimulus). The mean accuracy scores and standard deviations are described in Table 1. We found a significant effect of ACC ( $F(2,31) = 21.69$ ;  $P < 0.001$ ). Post-hoc tests revealed a significant difference in ACC between the SM and SP ( $P < 0.002$ ), DM and SM ( $P < 0.001$ ), and DM and SP ( $P < 0.001$ ) conditions. These differences resulted from higher accuracy in the SP condition than the SM condition and for the SM condition than the DM condition.

We examined task-switching effects by using a one-factor ANOVA with three levels (single-pure, single-mixed non-switch, single-mixed switch). The mean reaction times and standard deviations for each condition are described in Table 1. We found a significant effect of ACC ( $F(2, 32) = 11.63$ ;  $P < 0.001$ ). Post-hoc comparisons revealed a significant difference between SP and NSW tasks ( $P < 0.001$ ) and between SP and SW tasks ( $P < 0.001$ ) such that the SP condition was more accurate than either the SW or NSW conditions. There was no difference between NSW and SW conditions ( $P < 0.393$ ).

#### Neuroimaging data

##### Conjunction analysis between SP, SM, and DM conditions

First, because we were interested in utilizing the SP condition to examine preparatory effects with relation to the SM task, we calculated the mean effect of the two single-pure tasks for each participant and used these statistical maps for subsequent SP comparisons.

A pattern of activity throughout prefrontal, parietal, occipital, and temporal lobes was observed for all three conditions when compared to baseline. The conjunction analysis revealed that activity in all regions showed a large degree of overlap between the three conditions (see Table 2).

##### Brain regions active for non-switch condition versus baseline and switch condition versus baseline

Both of these comparisons are subsets of the SM condition. Therefore, it is not surprising that these comparisons revealed activation throughout the cortex that highly overlapped with the SM condition including prefrontal, parietal, temporal, and extrastriate cortices as well as subcortical structures.

##### Brain regions active for the direct comparison of the dual-mixed condition and single-mixed condition

This contrast was vital in revealing the areas of activation due to dual-task processing while controlling for effects of preparation between the conditions (see Table 3). Therefore, this contrast is a more conservative estimate of dual-task effects than a typical comparison between dual and single-task blocks because a comparison of a block composed entirely of dual-trials to another block composed entirely of single trials might result in activation associated with processes not essential in dual-task performance. In order to ensure that our comparisons were showing differences due to activation rather than deactivation, we used the activation from the dual-mixed versus baseline comparison as a mask for this contrast.

Although some studies report new regions of activation for the dual-task compared to the activation in single-task blocks, we found that once controlling for effects of preparation on brain activity, the areas of activation overlapped with the activation in the single-mixed condition including clusters in bilateral inferior, middle, and superior frontal gyri, anterior cingulate, inferior and superior parietal lobules, and inferior and superior parietal cortices, and a number of regions throughout occipital and temporal lobes (see Fig. 2). Furthermore, the conjunction analyses revealed that the areas that differed between the conditions were also active for all conditions versus baseline. This suggests that the difference between the conditions is a result of a difference in the magnitude of activation and not a result of the areas being “on” for the dual-task condition and “off” for the single-task condition. This result supports previous claims (e.g. Bunge et al., 2000) that dual-task operations do not require the activation of new regions, but instead engage the same regions as the single tasks, but simply to a greater degree.

##### Brain regions active for the direct comparison of the single-mixed condition and single-pure condition

This comparison was important in order to determine the brain regions associated with non-dual-task-related processes, such as preparation, in this paradigm (see Table 3). In order to ensure that we were examining regions associated with activation rather than deactivation, we used the activation pattern from the SM versus baseline comparison as a mask for this contrast.

As predicted, we found activation in regions that were separated from those regions reported in the comparison between the DM and SM conditions (see above). The extensive overlap in areas of activation in the present study and the findings reported in other studies that examine preparatory effects (e.g. Brass and von

Table 2  
Regions, coordinates, and peak Z-scores for the conjunction analysis between the SP, SM, and DM conditions versus baseline

Region	Conjunction of SP, SM, and DM			
	X	Y	Z	Z-score
<i>Frontal</i>				
R. anterior cingulate	5	21	28	6.16
L. inferior frontal gyrus	-39	17	-6	8.02
R. inferior frontal gyrus	37	23	-1	6.71
L. insula	-40	14	-5	7.52
R. insula	39	18	0	7.41
L. medial frontal gyrus	-6	5	48	6.02
R. medial frontal gyrus	1	7	48	6.06
L. middle frontal gyrus	-29	-9	50	6.25
R. middle frontal gyrus	27	-5	56	6.52
L. precentral gyrus	-49	1	27	5.88
R. precentral gyrus	43	-25	38	5.99
L. superior frontal gyrus	-4	3	52	5.03
R. superior frontal gyrus	-37	-49	20	5.32
<i>Temporal</i>				
L. inferior temporal gyrus	-45	-75	-6	5.43
R. inferior temporal gyrus	37	-73	-4	5.21
L. middle temporal gyrus	-31	-65	28	6.42
R. middle temporal gyrus	33	-67	28	6.65
L. superior temporal gyrus	-61	-31	20	6.61
R. superior temporal gyrus	33	-59	28	6.74
<i>Parietal</i>				
L. angular gyrus	-33	-57	36	9.75
R. angular gyrus	33	-63	36	9.43
L. inferior parietal lobule	-47	-43	50	8.70
R. inferior parietal lobule	31	-53	48	8.31
L. precuneus	-28	-61	42	8.11
R. precuneus	29	-53	50	9.15
L. superior parietal lobule	-35	-57	50	9.80
R. superior parietal lobule	31	-53	50	9.76
L. supramarginal gyrus	-43	-43	38	8.24
R. supramarginal gyrus	35	-49	38	7.61
<i>Occipital</i>				
L. cuneus	-17	-97	0	7.81
R. cuneus	9	-95	0	7.51
L. fusiform gyrus	-32	-69	-13	7.21
R. fusiform gyrus	33	-75	-19	6.74
L. inferior occipital gyrus	-33	-91	-5	7.11
R. inferior occipital gyrus	33	-83	-18	6.81
L. lingual gyrus	-1	-81	-15	6.71
R. lingual gyrus	33	-73	-15	6.90
L. middle occipital gyrus	-33	-93	-5	6.10
R. middle occipital gyrus	33	-75	-15	6.51
<i>Subcortical</i>				
L. putamen	-23	5	3	6.23
R. putamen	21	5	3	6.45
L. globus pallidus	-20	0	0	6.26
R. globus pallidus	19	0	2	6.54
L. caudate	-12	-2	14	5.62
R. caudate	11	4	15	6.31
L. hippocampus	-27	-23	-8	5.21
R. hippocampus	27	-17	-10	3.72
L. pulvinar	-19	-22	11	5.36
R. pulvinar	17	22	11	5.54

Cramon, 2002; Corbetta and Shulman, 2002; Sohn et al., 2000) argues that these effects are likely due to increased levels of preparation in the SM condition. These regions included the right inferior frontal gyrus and the right superior parietal cortex and precuneus regions (see Fig. 3). All of these regions have been associated with task, or response, preparatory processes (Brass and von Cramon, 2004; Corbetta and Shulman, 2002). In addition, some of these regions have been reported in previous dual-task studies (Herath et al., 2001; Jiang, 2004), which suggest that prior results might be related to preparation rather than dual-task processing per se. This possibility will be discussed in greater depth in the Discussion.

Table 3  
Results from the direct comparison between the dual-mixed (DM) condition and the single-mixed (SM) condition and results from the direct comparison between the SM condition and the single-pure (SP) condition

Region	DM > SM				SM > SP			
	X	Y	Z	Z-score	X	Y	Z	Z-score
<i>Frontal</i>								
R. anterior cingulate	7	21	28	3.55				
L. inferior frontal gyrus	-37	19	-5	4.36				
R. inferior frontal gyrus	35	23	-11	3.93	34	20	24	4.10
L. insula	-36	16	-5	4.28				
R. insula	37	16	-6	3.43				
L. middle frontal gyrus	-26	-11	58	5.06				
<i>Temporal</i>								
L. superior temporal gyrus	-55	1	5	4.72				
R. superior temporal gyrus	45	20	-12	3.28				
<i>Parietal</i>								
L. angular gyrus	-33	-55	36	3.47				
L. inferior parietal lobule	-41	-39	52	5.60	-35	-41	43	3.10
R. inferior parietal lobule	37	-31	44	6.02	47	-33	40	3.74
L. precuneus	-28	-57	54	5.36	-20	-61	56	4.94
R. precuneus	23	-55	54	5.16	5	-65	44	5.02
L. superior parietal lobule	-31	-55	54	5.42	-25	-59	56	5.57
R. superior parietal lobule	25	-53	48	4.63	21	-69	44	3.78
L. supramarginal gyrus	-47	-39	38	4.97				
R. supramarginal gyrus	41	-39	38	3.81				
<i>Occipital</i>								
L. cuneus	-24	-95	-4	4.44				
R. cuneus	11	-95	-1	4.95				
L. fusiform gyrus	-29	-69	-15	4.07				
R. fusiform gyrus	33	-77	-18	4.82				
L. inferior occipital gyrus	-31	-91	-5	5.09				
R. inferior occipital gyrus	35	-79	-11	4.37				
L. lingual gyrus	-26	-89	-9	4.44				
R. lingual gyrus	17	-81	-13	4.91				
<i>Subcortical</i>								
L. putamen	-24	8	-6	4.16				
R. putamen	17	8	-9	4.35				
L. globus pallidus	-19	-3	-7	3.80				
R. globus pallidus	17	-1	-1	4.12				
R. caudate	9	10	-6	3.36				
L. hippocampus	-27	-25	-10	3.57				
R. hippocampus	30	-19	-10	3.48				
R. pulvinar	14	-24	8	3.51				

The table shows the locations of the peaks and the Z-scores for each comparison.

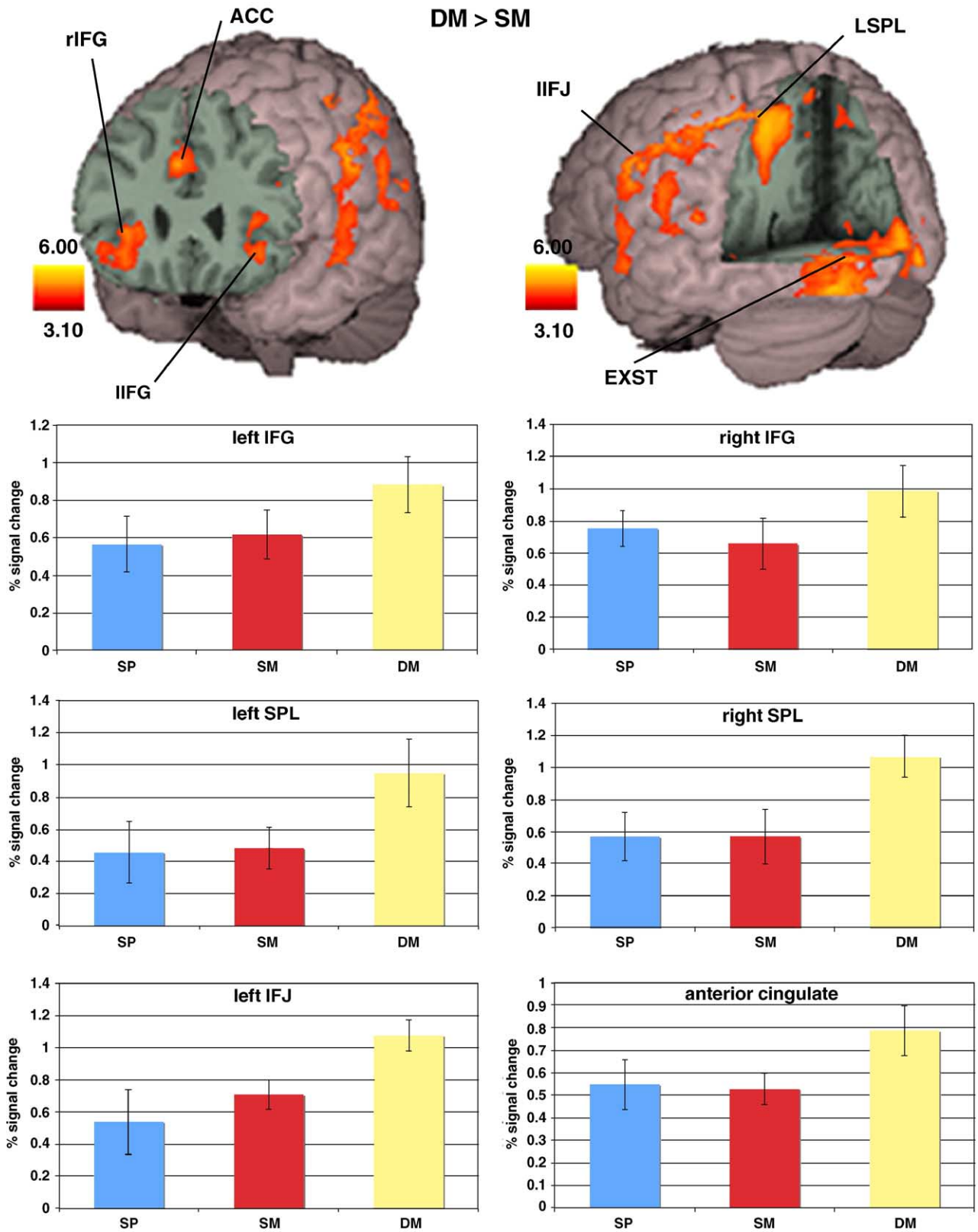


Fig. 2. Brain activation for the DM versus SM comparison using the DM versus baseline comparison as a mask to ensure that the statistical maps result from a difference in activation rather than a difference in deactivation. The brain figures show anterior cingulate (ACC), left inferior frontal gyrus (IIFG), right inferior frontal gyrus (rIFG), left superior parietal lobule (LSPL), extrastriate regions (EXST), and left inferior frontal junction (IIFJ). The bar graphs below show the percent signal change in six of the regions for this comparison for each of the three main conditions (single-pure (SP), single-mixed (SM), and dual-mixed (DM)).

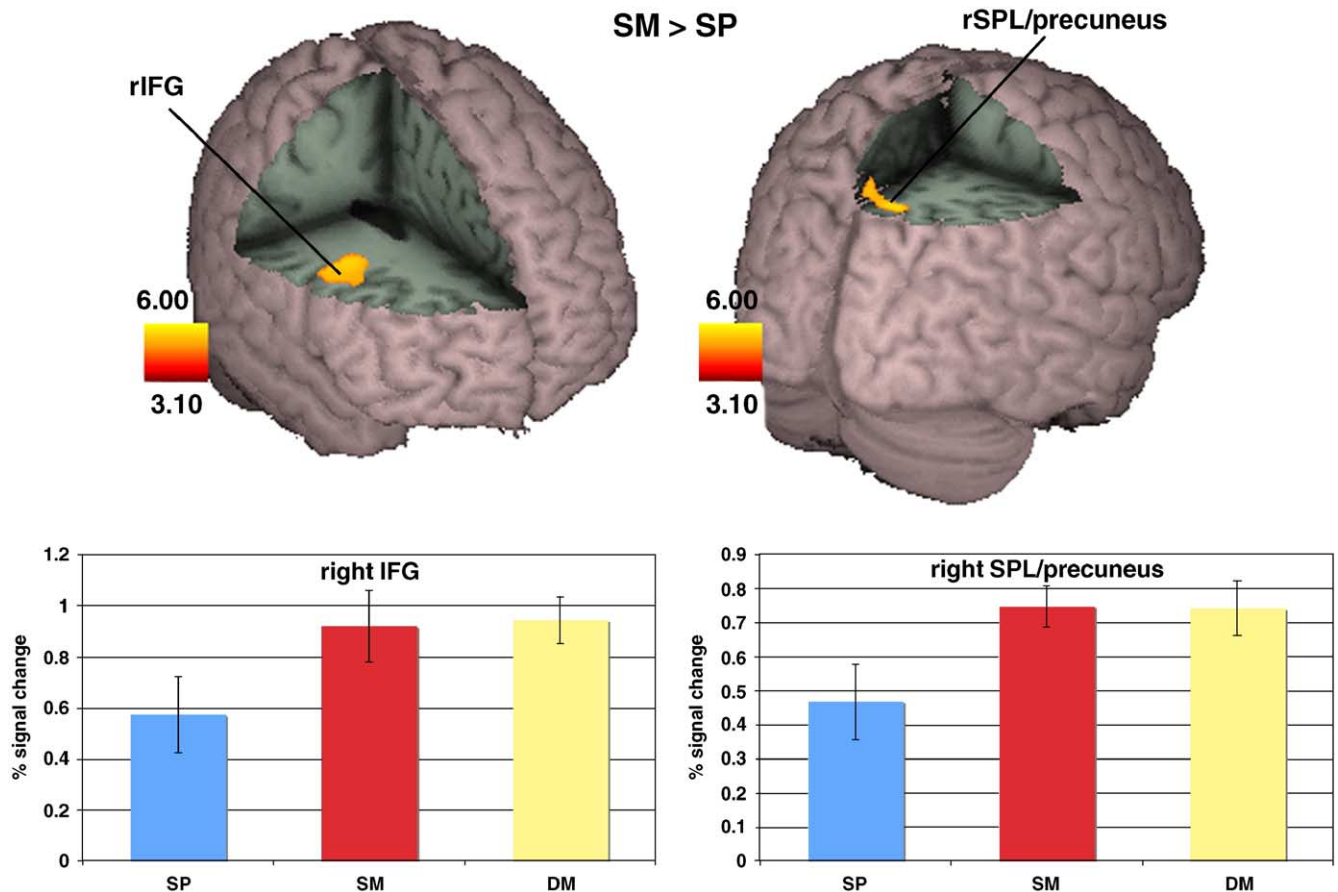


Fig. 3. Brain activation for the SM versus SP comparison using the SM versus baseline comparison as a mask to ensure that the statistical maps result from a difference in activation rather than a difference in deactivation. Regions shown include the right inferior frontal gyrus (rIFG) and right superior parietal lobule (rSPL) and precuneus. The bar graphs below show the percent signal change in both of these regions for each of the three conditions.

Prior studies have often reported preparatory activity in the premotor cortex (Adam et al., 2003), but we did not find any premotor activity in the SM versus SP comparison at our whole-brain threshold. It is possible that not much of the variance in the premotor cortex could be accounted for by preparatory processes, and our whole-brain threshold was too stringent to detect such an effect. Therefore, as a post-hoc analysis to assess whether premotor cortex showed greater activity for the SM comparison than the SP comparison, we lowered the voxel-wise threshold in this comparison to a Z-score of 1.96. The result of this adjustment revealed bilateral peaks of activation within the premotor cortex at Z-scores of 2.21 and 2.23 for the left and right premotor cortex respectively. This result provides post-hoc but supporting evidence that the SM condition involves sub-threshold premotor activity that is possibly related to a greater degree of task-preparatory processes than the SP condition.

#### *Brain regions active for direct comparison of single-task switch trials and non-switch trials within the mixed blocks*

The goal of this comparison was to examine the regions involved in task-switching within the mixed block of trials and to assess the overlap of these regions with the regions active in the SM versus SP comparison. If extensive regional overlap existed, then it would suggest that at least some of the activation in the SM versus SP comparison is due to greater task-switching demands present within the mixed block of trials. However, if the overlap between the two comparisons is minimal, then it provides additional

evidence that the areas of activation for the differences between the SM and SP conditions are due to greater preparatory demands rather than greater task-switching demands in the SM condition.

For this comparison, we found only two clusters of activation that were both located in the superior parietal lobule and precuneus (see Fig. 4). A similar parietal region has been reported in previous studies of the neural correlates of task-switching (DiGirolamo et al., 2001; Kimberg et al., 2000), however, many other studies commonly report additional areas of activation such as anterior cingulate (e.g. Dove et al., 1999) and prefrontal cortex (e.g. Sohn et al., 2000). The lack of much activation in this comparison may be due to the extensive activation already present in the non-switch trials. It is important to note that the parietal regions in this comparison did not overlap with the regions reported for the direct comparison between the SM and SP conditions (Table 4).

#### **Discussion**

In this study, we examined three main questions. First, we asked which brain regions were involved in dual-task processing in an event-related paradigm in which the effect of preparation between dual and single trials was minimized. Previous studies have not dissociated dual-task processing related areas from areas involved in the preparation of the two tasks and therefore may have misattributed activation variance. Similarly, we asked if any of the



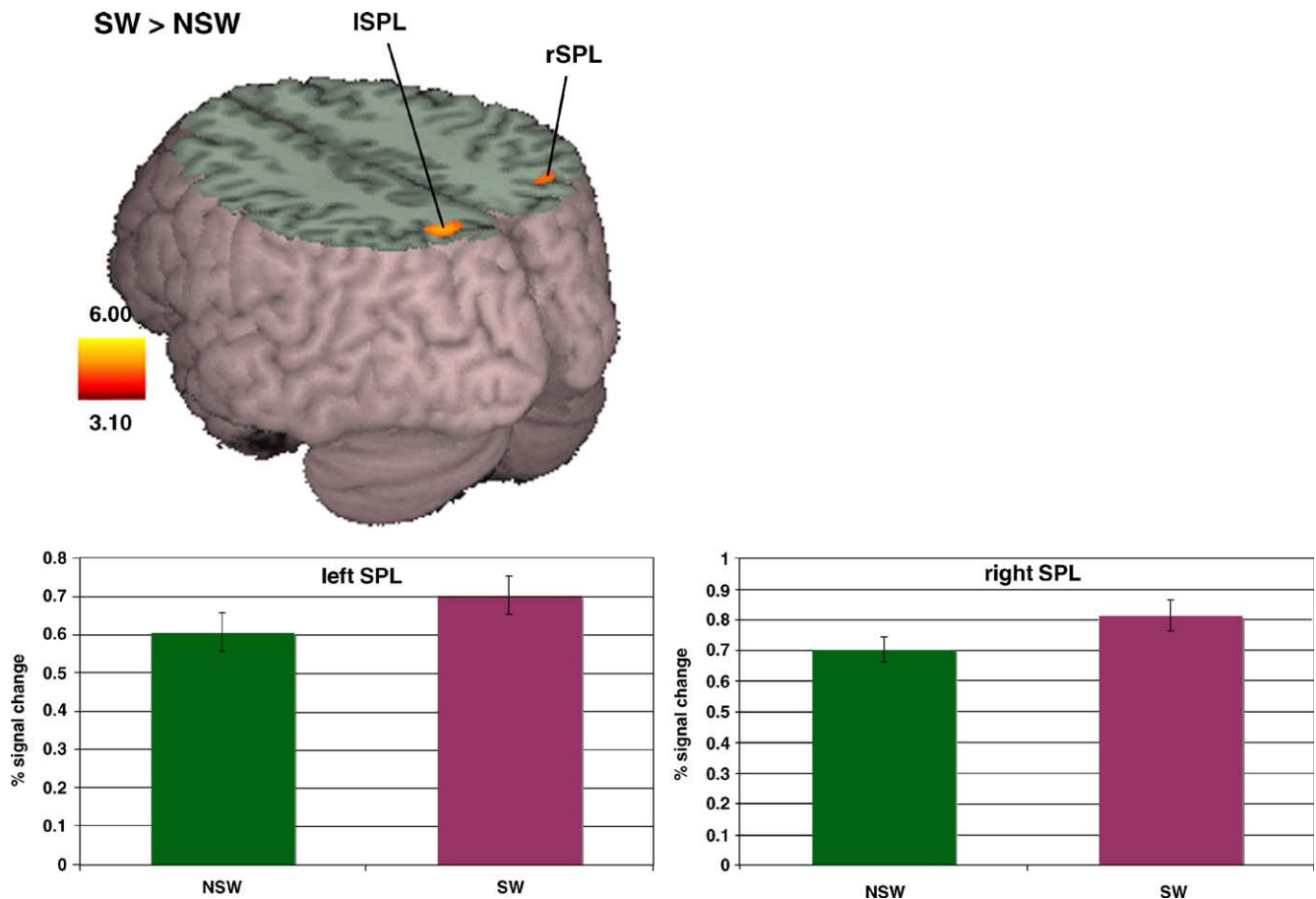


Fig. 4. The brain image shows the regions of activation for the SW versus NSW comparison using the SW versus baseline comparison as a mask to ensure that the statistical maps result from a difference in activation rather than a difference in deactivation. These regions included the left superior parietal lobule (rSPL) and left superior parietal lobule (ISPL). The bar graphs below show the percent signal change for each condition in each of the regions.

inferior prefrontal cortex that has recently been implicated in dual-task processing could be accounted for by single-mixed task operations. If the effects could be accounted for by SM task activity, then the function of the inferior frontal gyrus in dual-task performance might be related to processes involved in preparing two or more tasks rather than actually carrying out two concurrent tasks. Second, we asked if the activation during single-trials, when unpredictably intermixed with dual-trials, would result in a pattern of activation commonly reported in response or attention-related cuing preparation paradigms, thus lending support to the claim that this task requires increased preparation as compared to single-task performance in pure trial blocks. Third, we asked if any of the regions active in the direct comparison between SM and SP trials could be accounted for by task-switching demands inherent in the mixed block of trials.

Table 4  
Regions, coordinates, and peak Z-scores from the SW versus NSW comparison

Region	SW > NSW			
	X	Y	Z	Z-score
L. precuneus	-19	-69	46	4.34
R. precuneus	37	-67	45	3.59
L. superior parietal lobule	-21	-67	45	4.17
R. superior parietal lobule	35	-61	45	3.64

#### Dual-mixed versus single-mixed processing

Although numerous neuroimaging studies have examined the regions of activation associated with dual-task processing, these studies and comparisons were all conducted in block designs and have not accounted for differential effects of preparation on dual-task-related brain activity (Adcock et al., 2000; Bunge et al., 2000; D'Esposito et al., 1995; Herath et al., 2001; Jiang, 2004; Schubert and Szameitat, 2003). Therefore, the DM versus SM comparison is a more conservative estimate of the regions and magnitude of activation involved in dual-task processing.

First, we found reliable costs in both reaction time and accuracy when comparing dual-task trials and single-task trials within the mixed block (see Table 1). Thus, in replication of similar studies (e.g. Pashler and Johnston, 1998), we found a significant dual-task cost when single-task trials and dual-task trials were randomly intermixed.

In this comparison, we found bilateral ventral inferior prefrontal cortex activity that extended into the insula bilaterally. Importantly, the inferior prefrontal clusters were located ventral to the clusters, and peaks found for our effects of preparation and did not overlap with them (see below). This ventral prefrontal activation lends support to the claim that dual-task performance relies on executive functions mediated by the lateral prefrontal cortices. Previous dual-task studies have focused on activation in a more dorsal region of the inferior frontal gyri in dual-task paradigms in which the SOA is

manipulated (Herath et al., 2001; Szameitat et al., 2002; Schubert and Szameitat, 2003) but have come to disparate interpretations of the results. Herath et al. (2001) suggested that the right inferior frontal gyrus is involved in resolving response interference, while Schubert and Szameitat (2003) have argued that the left inferior frontal gyrus is engaged during response selection. Therefore, the exact role that the left and right inferior frontal regions are playing in dual-task processing is currently undecided. We speculate that these regions are engaged to a greater degree in managing and coordinating the performance of multiple tasks. However, an important point to consider is that these regions were also active for the SM condition relative to baseline and were simply more engaged for the DM condition. Therefore, based on the extant literature, it seems likely that these regions are involved in engaging attentional control operations which are increased during multi-task processing (MacDonald et al., 2000).

We also found other prefrontal cortex activity in this comparison including a cluster of activation in the dorsal left inferior and middle frontal gyrus (see Fig. 2) close to the left inferior frontal junction activation commonly reported in task-switching studies (e.g. Brass and von Cramon, 2002). Similar to the ventral prefrontal activation, the dorsal middle frontal gyrus cluster was located in a different prefrontal region than the effects related to preparation (see below). Furthermore, although the left dorsolateral prefrontal cluster of activation has not been reported in previous dual-task studies, this region has been frequently associated with working memory and attentional control processes and the engagement of top-down control on task-relevant posterior cortical systems (Banich et al., 2000) as well as task-coordination processes during task-switching and Stroop tasks (Brass and von Cramon, 2002; Derrfuss et al., 2004). Therefore, it is likely that this cortical region is involved in modulating posterior processing centers during the coordination of multiple task sets and responses in working memory (Derrfuss et al., 2004). This type of top-down cognitive control is essential for the successful completion of this task and is supported by evidence from recent studies that have investigated the effective connectivity between prefrontal and parietal structures (Erickson et al., 2005).

We also found extensive activation in the basal ganglia, which might be related to learning the correct stimulus–response mappings through a fronto-striatal cortical loop (Packard and Knowlton, 2002) or a greater engagement of regions involved with sequencing operations (Pashler and Shiu, 1999). There are at least two lines of research that support the claim that subcortical structures are important in dual-task performance. First, a study performed with patients who had undergone a surgical transection of the corpus callosum found that control participants and split-brain patients showed similar patterns of dual-task performance when each task was presented to a single hemisphere (Pashler et al., 1994). Equivalent dual-task performance between control and patients suggests an important role for subcortical structures in performing dual-task sequences (Pashler et al., 1994). Second, patients with Parkinson's disease and Huntington's disease, who have structural and functional deficits of the basal ganglia, are known to have significant deficits when performing two tasks simultaneously or in quick succession (Packard and Knowlton, 2002) and particularly when trying to sequence events in a dual-task paradigm (Brown and Marsden, 1991). These findings, along with our neuroimaging results, and others (Adcock et al., 2000) suggest that subcortical structures play an important role in dual-task performance.

A previous study reported extensive activation throughout the rostral anterior cingulate for a dual-task condition relative to a task-switch condition (Dreher and Grafman, 2003) and suggested that this region was playing an important role in resolving the conflict between stimulus–response associations. We, however, report a more dorsal anterior cingulate region similar to that found under conditions of heightened conflict such as in Stroop (Milham et al., 2001), flanker (Botvinick et al., 1999), and task-switching (DiGirolamo et al., 2001; Dove et al., 1999) tasks. Based on this literature and similar to Dreher and Grafman (2003), we argue that this region is involved in resolving, managing, or monitoring the greater potential for error in the dual-task condition.

We also found activation throughout the visual and extrastriate cortex (Fig. 2), even though the number of total items on the screen was equivalent for both the DM and SM conditions. It is possible that this visual cortex activation is representative of top-down processes influencing task-relevant visual operations (Beauchamp et al., 1997; Friston and Buchel, 2000) or could simply be that the placeholder star (\*) presented in the single trials did not engage the visual cortex to the degree of the task-relevant stimuli in the dual-task. In any case, the DM trials activated a network of extrastriate regions that are commonly implicated in attention and perceptual tasks (Corbetta et al., 1991).

The extensive parietal activation is also interesting considering that similarly located regions have well-established roles in attention (Corbetta and Shulman, 2002; Woldorff et al., 2004), working memory (Smith and Jonides, 1999), and executive processes (Woldorff et al., 2004). As discussed in the section on preparatory effects, Brass and von Cramon (2004) and others (Corbetta and Shulman, 2002) have suggested that the intra-parietal sulcal regions might be involved in selecting the stimulus–response associations necessary for task demands. From this perspective, it seems likely that dual-task conditions require increased engagement of regions involved in the selection of appropriate stimuli and responses because more stimulus–response associations are necessary to fulfill task demands. Therefore, we argue that the parietal regions are playing an important role in mediating stimulus–response associations and attending to behaviorally relevant stimuli.

There are a few other important conclusions we can draw from these results. First, consistent with most dual-task studies (e.g. Adcock et al., 2000; Bunge et al., 2000; D'Esposito et al., 1995; Herath et al., 2001; Schubert and Szameitat, 2003), we report extensive dual-task activation in prefrontal cortex, thus supporting previous claims that executive functions play an important role in performing concurrent tasks. Secondly, consistent with results from some studies (Adcock et al., 2000; Bunge et al., 2000) but inconsistent with results from other studies (Herath et al., 2001; Schubert and Szameitat, 2003), we find that the single task and dual tasks activate the same areas but that the dual tasks simply activate these areas to a greater degree. This result might mean that these regions need to be engaged more in order to manage the increased task load during dual-task performance, or instead, it might mean that increased activation in these regions during dual-task performance reflects a source of the response interference observed in dual tasks (Klingberg, 1998).

#### *Single-mixed condition versus single-pure task processing differences*

One of the important aspects of the SM versus SP comparison is that both types of trials require only a single response, but the SM

trials require the preparation of more than one response. In addition, the SM condition also involves other cognitive processes that are not engaged in the SP condition such as a higher working memory load and a greater need for cognitive flexibility in order to switch between tasks. Therefore, when comparing the SM trials to the SP trials, we can assess the behavior and brain regions that are involved in cognitive operations that are not essential in dual-task processing. However, for this comparison, we observe that the regions that are active are similar to those commonly found in studies that examine task-preparation (e.g. Brass and von Cramon, 2004). Therefore, it seems likely that our results are representative of heightened engagement of regions that are involved in preparing for two tasks in the mixed block relative to the need to prepare only one task during the pure blocks. The subthreshold premotor cortex activity obtained from the post-hoc analysis further supports this argument. However, it should also be noted that, since we did not assess cue-related activity, the preparation argument proposed in this paper should only be considered as preliminary evidence. A similar dual-task experiment with the addition of a cue would more explicitly test this argument and lend further support to our conclusions.

First, we found that reaction times were reliably longer in the SM condition than the SP condition, thus replicating other studies that have compared single-task trials within a mixed block with single-task trials within a pure block (e.g. Pashler and Johnston, 1998). We also found that activation in the SM versus SP comparison was localized to regions commonly associated with attentional preparation, thus providing support for the claims that (a) the increase in response time associated with this comparison is due to increased attentional preparation demands and (b) because similar regions have been reported in previous dual-task neuroimaging experiments, comparing blocks of trials that differ in either the number of tasks to be performed or comparing results from different SOAs (Dreher and Grafman, 2003) could result in neural activation associated with task-preparation not specific to dual-task processing.

One region found to be associated with our preparation contrast was the right prefrontal cortex including the inferior frontal gyrus, a region more dorsal to the cluster found in the DM versus SM comparison. Activity in the right prefrontal cortex has been reported in previous dual-task studies and been implicated in dual-task processes (Herath et al., 2001) and perceptual attention (Jiang, 2004). Our cluster of activation for the effects of preparation included one of two right inferior frontal gyrus locations ( $x = 46$ ,  $y = 6$ ,  $z = 26$ ) that were reported in a dual-task study by Herath et al. (2001) as well as peaks that were reported in dual-task studies by Jiang et al. (2004) and Jiang (2004). Since all three of these studies find peaks that overlap with the region that we find is active in the SM condition, this suggests that this region is not necessarily involved in dual-task processing but might instead be involved in some component of task-preparation.

Although the right inferior prefrontal cortex is commonly associated with executive functions (Milham et al., 2001) and response selection processes (van Veen et al., 2001), it has also been recently implicated in task-preparation (Brass and von Cramon, 2004; Dreher et al., 2002; Sohn et al., 2000). Although Brass and von Cramon (2004) reported activity in the right inferior frontal gyrus for a pre-cue to a stimulus, they suggested that this activity was not directly related to task-preparation but resulted from the competition of two task sets in working memory. Sohn et al. (2000), however, argued that the right inferior frontal gyrus is involved in endogenous components of task-preparation in a task-

switching paradigm when participants had foreknowledge of an upcoming switch or repetition trial. In support of both of these claims, we find that the dorsal right inferior frontal gyrus (near the pars triangularis of the frontal operculum) is involved in preparing for two-tasks relative to preparing for only one. However, our results also differ from some studies that suggest that the right inferior frontal gyrus is involved in task-preparation only when the sequence of the stimuli is predictable (Dreher et al., 2002; Sohn et al., 2000). Our results suggest that this region is involved in task-preparation even when the task sequence is unpredictable. Furthermore, in support of the claim by Brass and von Cramon (2004), we suggest that the greater degree of activity in the SM versus SP comparison in the right inferior prefrontal region is due to increased working memory demands for the greater preparatory state in order to maintain a greater number of potential responses and response mappings in working memory. This hypothesis would be consistent with working memory (Smith and Jonides, 1999) and attentional control research (Banich et al., 2000) and would suggest that this region is involved in holding the response set in working memory buffers so that other regions involved in response preparation can be engaged and maintained.

Bilateral superior parietal lobules have also been previously associated with attentional preparation regardless of the visual field in which attention is directed (Corbetta et al., 2000; Corbetta and Shulman, 2002; Shulman et al., 1999). We also find that similar parietal regions are active in our comparison to isolate preparation. Many of the studies that have examined preparatory effects in these regions have used spatial attention tasks in which a cue directs attention to some location in space (Corbetta and Shulman, 2002). Consistent with this idea, one difference between the SM condition and the SP condition is that the SP condition requires the direction of attention to only one location, whereas the SM condition requires spatial attention to be more distributed. In summary, these regions may be involved in attentional preparation and lend preliminary support for the claim that preparation processes are involved in dual-task performance.

#### *Single-task switch vs. non-switch trials in mixed trial blocks*

Although the areas of activation in the SM versus SP comparison overlap with areas commonly reported in studies on preparation, explanations other than preparation may exist for these effects. For example, task-switching processes are one additional component inherent within a mixed block of trials not present in pure blocks of trials. Therefore, higher activation for the SM condition relative to the SP condition could be due to greater task-switching demands for the SM condition. In order to test if task-switching processes could explain, in whole or in part, the areas of activation found in the SM versus SP comparison, we analyzed the single trials within the mixed block as either non-switch or switch trials. We reasoned that if any of the activation from the SM versus SP comparison were due to task-switching processes, then the regions of activation for the SM versus SP comparison would overlap with the results from the task-switching analysis.

We found that the task-switching results were limited to the superior parietal lobule and precuneus and did not overlap with the regions found for the SM versus SP comparison. Therefore, task-switching processes cannot explain the activation resulting from the SM versus SP comparison.

It should be noted, however, that the task-switching demands in this study were conceptually and methodologically different

than other task-switching studies, which could have led to the reduced task-switch cost seen in this study. For example, in most task-switching paradigms, the stimuli and responses are bivalent such that the target and response are relevant for both tasks (Meiran, 2000). In this study, the stimuli and responses are univalent such that they do not have overlapping or conflicting dimensions. This may explain the lack of a reliable task-switch cost and fewer brain regions activated for the switch as compared to the non-switch trials for the present as compared to previous studies (e.g. Braver et al., 2003).

### Summary

In summary, we found a large network of brain regions involved in dual-task processing even after minimizing the effects of preparation. These regions included the left and right ventral inferior prefrontal cortex, dorsal anterior cingulate, left and right inferior parietal and superior parietal lobules, and subcortical regions. These regions seem to be important in managing and coordinating response selection and execution of multiple tasks. We believe that it is important to note that our results suggest that there is not one center of activation specific to the coordination of multiple tasks, but a distribution of areas. We also found that the slowing of single-task responses in a mixed block of dual and single trials resulted in a pattern of activation that overlapped with regions commonly implicated in task-preparation including the right inferior prefrontal cortex. This suggests that results from some dual-task studies could have been confounded by activation due to preparatory differences between single and dual-task blocks. In addition, an analysis of the single trials within the mixed block revealed that task-switching processes could not fully account for the activation in the SM versus SP comparison, thus lending greater credence to the possibility that the difference between the SM and SP conditions is due to greater preparatory demands in the SM condition. Finally, we find that the brain regions active for the dual-task condition in the mixed block highly overlap with regions found to be active for each of the single tasks and that the areas simply increase in magnitude with greater processing demands. These results are important in understanding dual-task-related activity and the effects of task-preparation on dual-task processing.

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