Research Article

Functional Magnetic Resonance Imaging Provides New Constraints on Theories of the Psychological Refractory Period

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ABSTRACT—*We used functional magnetic resonance imaging (fMRI) to investigate the psychological refractory period (PRP), the delay in the response to the second of two tasks occurring in immediate succession. Our results were consistent with prior work on the PRP in that when two visual-manual tasks were presented within 100 ms of each other, the second response was delayed on the order of 500 ms, compared with when the two tasks were separated by 1,500 ms. Surprisingly, in brain regions postulated to be important for executive functions, there was virtually no increase in brain activation in the short-interval compared with the long-interval condition. These data suggest that passive queuing, rather than active monitoring, occurs during the PRP.*

In today's fast-paced society, people often find themselves wishing that there were 48 hours in a day, or that they could do two things at a time. Yet carrying out two tasks concurrently is almost as difficult as finding 48 hours in a day. The psychological literature shows that dual-task interference (Kahneman, 1973) is most striking when the processing for the two tasks overlaps at the response-selection stage, when percepts are mapped onto corresponding responses. The delay in the response to the second of two consecutive tasks, or *psychological refractory period* (PRP), is observed even when the input and output modalities differ for the two tasks. Thus, although people can see a shape and hear a tone at the same time, and can press a key and say a word at the same time, they cannot simultaneously determine which key to press on the basis of the shape and which word to say on the basis of the tone (Pashler, 1990; Levy & Pashler, 2001; Van Selst, Ruthruff, & Johnston, 1999; for demonstration of a significant reduction in interference after practice, see Schumacher et al., 2001). In the study we report here, we used functional magnetic resonance imaging (fMRI) to test why the PRP occurs and what processes go on during the delay.

How does cognitive and neural processing differ when two tasks compete for access to the response-selection bottleneck compared with when they do not? *Passive-queuing* accounts and *active-monitoring* accounts provide different answers to this question. According to passive-queuing accounts, while the central bottleneck is occupied by Task 1, Task 2 is held in a passive queue until the bottleneck is freed from Task 1. On this assumption, the total amount of cognitive processing should be roughly equivalent[1] whether the two tasks are presented within a short stimulus-onset asynchrony (SOA) or a long SOA. Alternatively, according to active-monitoring accounts, when two tasks are presented within a short SOA, substantial active monitoring is required to (a) determine the order in which the two tasks are processed, (b) monitor the progress of Task 1, (c) halt processing of Task 2 and hold it in working memory, and (d) determine when to resume Task 2. Thus, according to such accounts, significantly increased central executive functions are required in the short-SOA compared with the long-SOA condition, and the PRP delay reflects the increased processing time for such active monitoring.

The present study tested whether dual-task interference arises because of passive queuing or active monitoring (i.e., increased central executive processing). Because both can result in a delay in response, it is difficult to answer this question decisively with behavioral measures alone. However, neuroimaging provides an ideal tool to address this question: Increased central executive processing

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[1]Because of the prolonged reaction time for Task 2, subjects would have to maintain the percept of that task for a longer period of time during the short-SOA than during the long-SOA condition, but such maintenance is expected to be unsubstantial in simple choice reaction time tasks.

should entail greater brain activation for short than long SOAs, despite the fact that the two component tasks are identical in the two cases. A passive-queuing account predicts little or no increased activation for short compared with long SOAs.

Two recent studies have tested the short-SOA condition. Szameitat, Schubert, Muller, and von Cramon (2002) contrasted a dual-task short-SOA condition with a condition in which each task was performed alone and observed a significant increase in activation in bilateral middle frontal gyri and other regions. They suggested that the neural correlate of the PRP effect is in brain regions important for executive processes. However, because subjects needed to perform two tasks in the short-SOA blocks but one task in the single-task blocks, the difference in activation might have been due to the requirement to maintain two task sets rather than to the PRP effect. Herath, Klingberg, Yong, Amunts, and Roland (2001) compared short-SOA and long-SOA conditions and observed a significant increase in blood-oxygenation-level-dependent (BOLD) activation in right inferior frontal gyrus (GFi) during the short-SOA condition. But the two component tasks used were simple reaction time (RT) tasks, in which performance was determined primarily by the predictability of the timing of the stimuli rather than by response selection (Pashler, 1994). The SOA effect observed by Herath et al. may reflect a difference in preparatory state rather than competition for access to the bottleneck. Thus, to date, there is no conclusive evidence on whether the PRP is produced primarily by increased executive control or by passive queuing.

EXPERIMENT 1

In this study, we used fMRI to identify brain regions engaged more strongly when two tasks are conducted at short than at long SOAs. The SOA conditions were tested in two separate blocks. Each block lasted 48 s and included 16 dual-task pairs presented at a rate of 3 s per pair. The SOA between Task 1 and Task 2 was either 1,500 ms or 100 ms (Fig. 1). The two conditions had the same total number of task operations in a block, differing only in the spacing of the tasks within the block. In Task 1, subjects used their left hand to report a shape. In Task 2, using their right hand, some subjects reported the identity of a letter, and others reported the color of a cross.

We concentrate on the contrast between the short and long SOAs. Finding only minimal differences in brain activation between the two SOA conditions would support the hypothesis that the PRP is produced primarily by passive queuing. In contrast, if we found a significant increase in brain activation in the short-SOA condition in brain regions known to be important for executive functions, the results would indicate that the increased RT for Task 2 in that SOA condition is accompanied by significantly increased central executive control. Further, such activation would be correlated with the magnitude of the PRP effect on RT—the longer the postponement, the larger the activation difference (Herath et al., 2001).

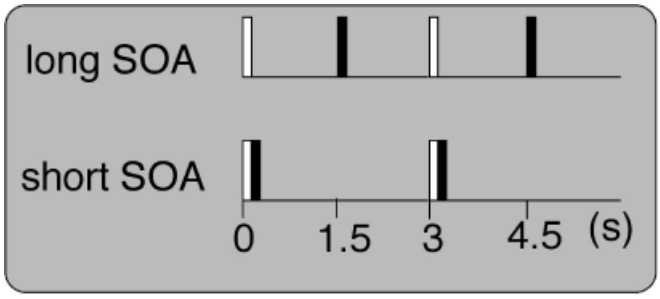

Fig. 1. Temporal sequence for the conditions with long and short stimulus-onset asynchronies (SOAs). White bars represent the display duration for Task 1, and black bars represent the display duration for Task 2.

Method

Subjects

Twenty-six subjects (18–42 years old) participated in this study. They had normal or contact-corrected visual acuity and normal color vision.

Testing Procedure

Subjects performed 20 min of practice before the scan. They were scanned on a Siemens 3.0-T head-only scanner at the Martinos Center for Biomedical Imaging (Charlestown, Massachusetts). During the functional scans, 20 axial slices 6 mm thick were scanned for 8 subjects, and 28 axial slices 4 mm thick were scanned for the others. Slices covered the entire brain except the lower portion of the cerebellum. There were four to six functional scans.

Scan Composition

Each functional scan used a blocked design with task conditions interleaved with fixation and instruction periods. For 15 subjects, fixation lasted 16 s and instruction lasted 4 s; for the others, fixation lasted 14 s and instruction 2 s. Following the fixation and instruction periods was the first task block of 48 s. Then the second fixation period was presented, followed by an instruction and a 48-s task block, and so on. A final fixation period of 20 s (or 16 s) followed the last task. The order of tasks was counterbalanced within subjects across different scans. In addition to the short-SOA and long-SOA conditions were other conditions irrelevant to the current report.

Materials and Tasks

Stimuli were presented using the Psychphysics Toolbox (Brainard, 1997) implemented in MATLAB. Presentation of the stimuli was synchronized with scanning.

On each display, one central item (Task 1: square or circle; Task 2: *A* or *B*, or a red or green cross, "+") and eight peripheral items (one square or circle and seven triangles; one *A* or *B* and seven pound signs, "#"; or one red or green cross and several mixed-color crosses) were presented. The peripheral items were evenly distributed on an imaginary circle with a radius of 3.75°. They were used as a control for a different experiment and were irrelevant to the current study. Subjects were instructed to attend to the center item and respond as accurately and as quickly as possible to both tasks. Each display was presented for 100 ms.

Task 1 was to press "1" for a square and "2" for a circle using the left hand. Task 2 was a letter-discrimination task for 15 subjects—press "3" for *A* and "4" for *B*—and was a color-discrimination task for the other 11 subjects—press "3" for a red cross and "4" for a green cross; the right hand was used to respond for Task 2. The dual tasks were presented at a rate of 3 s per pair. The SOA between the two tasks was either 1,500 ms or 100 ms.

fMRI Data Analysis

Data were analyzed using SPM99. Each subject's data were motion corrected, normalized onto the Montreal Neurological Institute template, smoothed with a Gaussian filter (full width at half maximum = 5 mm), and high-pass filtered during analysis. A random-effects analysis ($p < .001$ uncorrected with an extension threshold of 5 voxels) was carried out on the subtraction of activation for the long SOA from activation for the short SOA. The threshold was set to be relatively lenient to increase statistical power.

In addition to the whole-brain analysis, we conducted comparisons of short- versus long-SOA conditions in regions of interest (ROI) that have been shown in previous work to be involved in executive processes such as task preparation, monitoring, or switching. Each ROI was centered on the voxel that showed peak activation in past studies and included a spherical volume of 33 voxels within a 6-mm radius of the peak voxel. The ROIs were pre-supplementary motor area (pre-SMA; Rushworth, Hadland, Paus, & Sipila, 2002), dorsolateral prefrontal cortex (DLPFC; MacDonald et al., 2001), anterior cingulate cortex (ACC; MacDonald, Cohen, Stenger, & Carter, 2000), right posterior GFi (Konishi et al., 1998), anterior-dorsal prefrontal cortex (Nagahama et al., 2001), left and right GFi (Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000), left intraparietal sulcus (Dove et al., 2000), left superior parietal lobule (Kimberg, Aguirre, & D'Esposito, 2000), left and right middle frontal gyrus (Szameitat et al., 2002), and right GFi (Herath et al., 2001). If a significant amount of executive control is needed during the PRP, we would observe increased activation in the short- relative to the long-SOA condition in at least some of these ROIs.

Percentage signal change (PSC) relative to the fixation baseline was calculated for each task within each ROI for each subject.

Results

Behavioral Data

Mean accuracy was not influenced by the SOA manipulation (Table 1). However, reducing the SOA between the two tasks from 1,500 ms to 100 ms significantly increased RTs, by 222 ms on Task 1 and by 421 ms on Task 2, $ps < .0001$ (Table 1). The slowing in Task 1 RT likely occurred because our instructions gave nearly equal priority to the two tasks (see also Herath et al., 2001; Levy & Pashler, 2001; Ruthruff, Pashler, & Klaassen, 2001; Schumacher et al., 2001), so that Task 2 interfered with Task 1. Further evidence that Task 2 was waiting for the completion of Task 1 in the short-SOA condition came from within-subjects correlations between Task 1 and Task 2 RTs: The correlation was .89 when the SOA was 100 ms and .35 when the SOA was 1,500 ms, $p < .001$ (Table 1). The faster was the response to Task 1, the shorter was the delay of Task 2, a finding consistent with the notion of a central bottleneck (Pashler, 1994; but see Navon & Miller, 2002).

fMRI Data

Statistical Parametric Map: Short SOA > Long SOA. A random-effects analysis ($p < .001$ uncorrected) revealed significantly higher activation for the short- than the long-SOA condition in right GFi ($x = 51$, $y = 12$, $z = 15$), $t(25) = 4.98$, with 9 voxels. When the threshold was lowered to $p < .005$ uncorrected, a region in the right inferior parietal lobule (IPL; $x = 42$, $y = -39$, $z = 45$) became significant, $t(25) = 3.81$, as did a region in the post central gyrus (GPoC; $x = 27$, $y = -36$, $z = 66$), $t(25) = 3.57$.

A region that is involved in central executive control should show activation that is correlated with the amount of PRP interference (Herath et al., 2001). We tested the within-subjects correlation between the size of the SOA effect in fMRI activation, (short − long SOA), and the size of the RT interference effect, [short SOA(RT1 + RT2) − long SOA(RT1 + RT2)]/[long SOA(RT1 + RT2)]. The PSC was calculated from voxels that showed significantly more activation in the short- than the long-SOA condition, within a spherical volume centered on the peak voxel and having a 9-mm radius. Figure 2 shows the scatter plot of the correlation across subjects. The correlation coefficient was .05, $p > .50$, in the IPL; −.13, $p > .50$, in the GPoC; and −.37, $p < .066$, in the GFi. Because the IPL and GPoC activations were detected at an unusually low threshold and were not correlated with behavioral interference, we do not consider them further. However, larger behavioral interference tended to be associated with less SOA-related activation in right GFi.

The reverse subtraction, (long − short SOA), revealed a significant difference in medial frontal gyrus (Area 9). However, this effect was driven primarily by deactivation in the short-SOA condition compared with fixation and was not correlated with RT interference, $p > .40$.

ROI Analysis. We tested 12 regions that previous MRI studies indicated are important for executive functions. These regions included dorsal and ventral PFC, ACC and pre-SMA, and the parietal cortex (Table 2). A t test between the long- and short-SOA conditions revealed no statistical significance in any of the ROIs, all $ps > .10$ (uncorrected).

TABLE 1
Behavioral Performance in Experiment 1

Measure	Long SOA	Short SOA	Short SOA − long SOA (effect size[a])	*SE*(*D*)	*p*
Accuracy: Task 1	95.8%	95.9%	0.1%	1%	> .50
Accuracy: Task 2	96.4%	95.9%	−0.5%	1%	> .50
RT1	615 ms	836 ms	222 ms (.684)	28 ms	< .0001
RT2	582 ms	1,003 ms	421 ms (.832)	35 ms	< .0001
r(RT1, RT2)	.35	.89	.54 (.886)	.04	< .0001

Note. RT1 = Task 1 reaction time; RT2 = Task 2 reaction time; SOA = stimulus-onset asynchrony; *SE*(*D*) = standard error of the difference score.
[a]Effect size is measured by η_p^2.

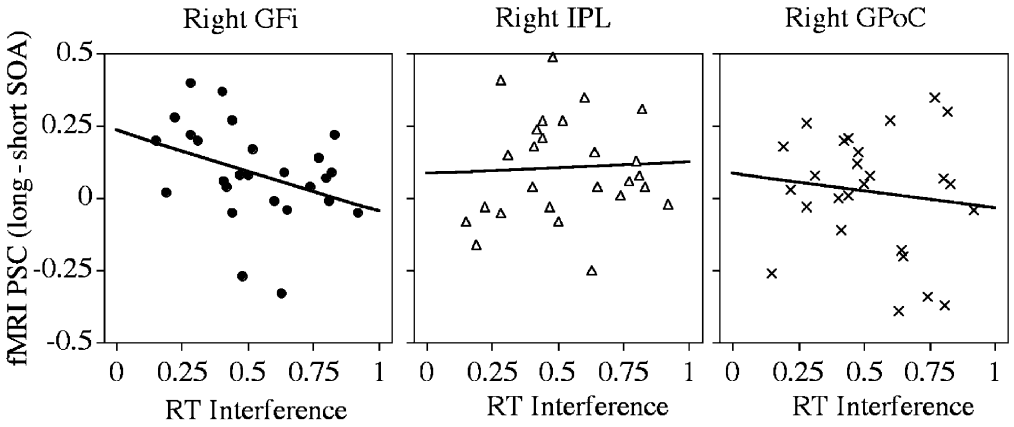

Fig. 2. Scatter plot of the correlation between the effect of stimulus-onset asynchrony (SOA) on reaction time (RT) and on functional magnetic resonance imaging (fMRI) activation. The left panel shows data from the right inferior frontal gyrus (GFi), the middle panel shows data from the right inferior parietal lobule (IPL), and the right panel shows data from the right post central gyrus (GPoC). Each point represents a single subject. PSC = percentage signal change.

Discussion

Compared with a long SOA of 1,500 ms, an SOA of 100 ms led to a dramatic interference of 222 ms in Task 1 and 421 ms in Task 2. Yet strikingly, this large RT cost was not accompanied by a significant increase in activation for the short-SOA condition in brain regions important for executive control.

This finding is unlikely to be due to a lack of statistical power. According to a recent estimate by Desmond and Glover (2002), to achieve high statistical power of .80 with an effect size of 0.5%, one needs to test approximately 24 subjects for a single voxel to reach significance at $p < .001$ in a random-effects analysis. Here we tested 26 subjects and adopted a lenient threshold of $p < .001$ (uncorrected), which should have provided us with high statistical power. Power was further increased in the ROI analysis, yet no regions passed the significance level of $p < .05$ (uncorrected). Finally, the ROIs we tested were sensitive to other experimental manipulations run in the same subjects and scans. For example, pre-SMA showed significantly higher activation for choice than for simple RT tasks, left GFi and left

TABLE 2

Percentage Signal Change From Fixation in 12 Regions Known to Be Important for Executive Functions: Experiment 1

Study and region	Talairarch coordinates			Long SOA	Short SOA
	x	*y*	*z*		
Rushworth, Hadland, Paus, & Sipila (2002)					
Left pre-SMA	−10	9	53	.31	.26
MacDonald, Cohen, Stenger, & Carter (2000)					
Left DLPFC	−41	18	28	.03	.02
ACC	4	1	43	−.03	−.04
Konishi et al. (1998)					
Right GFi	39	15	22	.03	.08
Nagahama et al. (2001)					
ADPFC	34	50	16	.01	.03
Dove, Pollmann, Schubert, Wiggins, & von Cramon (2000)					
Left GFi	−44	5	37	.36	.33
Right GFi	40	8	36	.17	.19
Left IPS	40	−32	−50	.28	.28
Kimberg, Aguirre, & D'Esposito (2000)					
Left SPL	−30	−79	48	−.37	−.36
Szameitat, Schubert, Muller, & von Cramon (2002)					
Left GFm	−44	16	38	.06	.00
Right GFm	41	30	32	.04	.03
Herath, Klingberg, Yong, Amunts, & Roland (2001)					
Right GFi	46	6	26	.19	.24

Note. $N = 26$. None of these regions produced a significant difference between short and long stimulus-onset asynchronies, all $ps > .10$. SOA = stimulus-onset asynchrony; pre-SMA = pre-supplementary motor area; DLPFC = dorsolateral prefrontal cortex; ACC = anterior cingulate cortex; GFi = inferior frontal gyrus; ADPFC = anterior-dorsal prefrontal cortex; IPS = intraparietal sulcus; SPL = superior parietal lobule; GFm = middle frontal gyrus.

intraparietal sulcus and superior parietal lobe showed significantly higher activation for dual tasks (long SOA) than single tasks (Jiang & Kanwisher, 2003), and several prefrontal regions showed significantly higher activation when subjects responded to a peripheral target than to a central target (Jiang & Kanwisher, 2003). The delay in RT produced by the PRP effect was considerably larger than the delay caused by, for example, choice (relative to simple) RT tasks (M = 120 ms), yet activations were greater for choice versus simple RT than for the PRP effect. Thus, to the extent that a smaller RT difference had a corresponding activation in brain imaging, the lack of brain activation associated with the PRP effect cannot simply be attributed to the insensitivity of fMRI.

These results pose a challenge to active-monitoring accounts of the PRP, because they predict increased processing demands for the short-SOA condition. Any such extra processing demands, if they exist, did not produce measurable increases in brain regions important for executive functions. Our results are consistent with passive-queuing accounts of the PRP, according to which the RT cost on Task 2 at short SOAs reflects not extra processing but passive queuing.

EXPERIMENT 2

In Experiment 1, the SOA manipulation did not activate brain regions important for executive functions. However, we did find significantly higher activation for the short than the long SOA in right GFi. This activation was negatively correlated with behavioral interference. It is unlikely that the GFi activation corresponded to executive processes, because the longer Task 2 is delayed, the longer any monitoring process is required, so there should be a positive, rather than a negative, correlation between RT interference and fMRI activation in regions important for executive processing during the PRP (Herath et al., 2001).

We propose, instead, that the GFi activation may have arisen because some subjects tried harder in the short- than the long-SOA condition, so as to reduce the postponement of Task 2. Subjects who try harder should show reduced RT interference but increased GFi activation compared with those who adopt a more relaxed mode.

To test whether the right GFi activation in Experiment 1 was due to a difference in strategy or due to PRP postponement per se, in Experiment 2 we used a within-subjects design and instructed subjects to adopt two different strategies. In blocks with the *conservative strategy*, subjects were asked to respond at a normal, comfortable pace, and to carry out the two tasks sequentially. In blocks with the *daring strategy*, subjects were asked to respond as fast as possible for both tasks and not to slow down Task 2 because of Task 1 (Schumacher et al., 2001).

Method

Participants

Twelve subjects were tested. Five of them had also participated in Experiment 1.

Design

A 2 × 2 blocked design was used: two strategies (conservative, daring) × two SOAs (long, 1,500 ms; short, 100 ms). The resulting four conditions were presented to subjects in a random order within each scan. Each block lasted 48 s, preceded by a fixation block of 16 s and an instruction of 4 s. Each subject participated in six to eight scans. Because of a computer error, behavioral data were recorded during scanning of only 2 of the 12 subjects. Behavioral data from the other 10 subjects were taken from a retest after the fMRI session. Because these subjects were more practiced during the postscanning session, we also collected behavioral data from 10 new subjects who were as practiced as the fMRI subjects were during the scan. The RT patterns (effects of SOA and strategy) were similar in the two groups of subjects. Thus, the behavioral data collected after scanning were a good approximation to the performance during the scan.

Results

Behavioral Data

Both strategy and SOA significantly influenced performance (Table 3). Presenting the two tasks within a short SOA produced a significant interference of about 200 ms in Task 1 RT under both strategies. The

TABLE 3
Behavioral Data From Experiment 2

	Conservative strategy		Daring strategy		Significance level		
Measure	Long SOA	Short SOA	Long SOA	Short SOA	Strategy main effect	SOA main effect	Interaction
Accuracy: Task 1	97%	97%	94%	97%	$p < .05$ (.419)	$p < .02$ (.621)	$p < .05$ (.432)
Accuracy: Task 2	95%	94%	90%	80%	$p < .001$ (.670)	$p < .10$ (.185)	$p < .05$ (.251)
RT1	618 ms	799 ms	478 ms	699 ms	$p < .001$ (.654)	$p < .001$ (.623)	n.s. (.209)
RT2	622 ms	1,054 ms	466 ms	743 ms	$p < .001$ (.713)	$p < .001$ (.900)	$p < .01$ (.504)
r(RT1, RT2)	.42	.85	.39	.87	n.s. (.050)	$p < .001$ (.856)	n.s. (.154)

Note. Effect sizes (η_p^2) are in parentheses. RT1 = Task 1 reaction time; RT2 = Task 2 reaction time; SOA = stimulus-onset asynchrony.

interference of 432 ms in Task 2 RT under the conservative strategy was reduced to 277 ms under the daring strategy, but at a cost of accuracy (10% accuracy drop, compared with a drop of 1% under the conservative strategy). The sizable remaining interference (277 ms) and the clear speed-accuracy trade-off suggest that subjects were unable to conduct the two tasks in parallel, even when the instructions asked them to do so.

fMRI Data

A random-effects analysis on the 12 subjects revealed no voxels passing the threshold of $p < .001$, uncorrected, for the main effect of SOA. The main effect of strategy was significant at this threshold in several regions (Fig. 3): bilateral middle frontal gyrus, ACC and pre-SMA, bilateral thalamus, left intraparietal sulcus, and cerebellum. Thus, increasing mental effort alone is sufficient to activate regions known to be important for attentional control.

Regions that showed a significant interaction test—greater effects of PRP in the daring than the conservative strategy—included a cluster of 6 voxels in right GFi ($x = 54$, $y = 12$, $z = 9$), $t(11) = 5.40$, and a cluster of 7 voxels in the white matter bundle in the left frontal cortex (Fig. 4). The GFi activation was adjacent to the frontal cluster ($x = 51$, $y = 12$, $z = 15$; 6.7 mm) found in Experiment 1. No regions showed a significantly greater SOA effect with the conservative than with the daring strategy.

Thus, the GFi activation may reflect the fact that subjects tried harder during the short- than the long-SOA condition when they were compelled to adopt a daring response strategy. In other words, the queuing of response selection itself is largely passive, but the effort to reduce the postponement is active. The latter effort is under strategic control, although it reduces postponement only at a cost of impaired accuracy. The inability to effectively reduce the PRP delay may explain why subjects tend not to adopt a daring response strategy on their own, at least not without extensive practice.

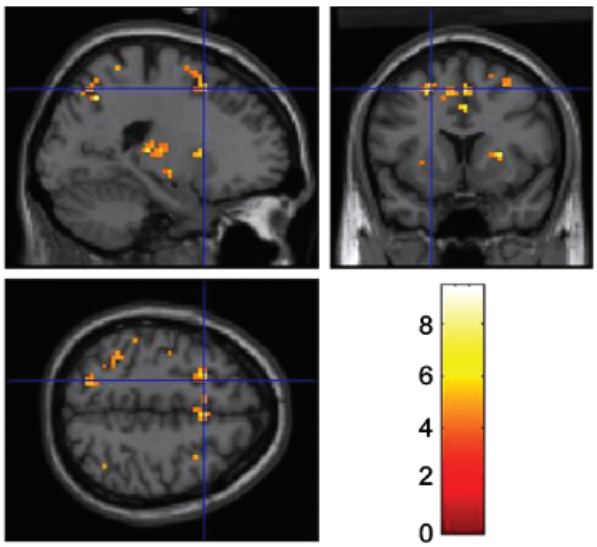

Fig. 3. Brain regions activated by adopting the daring strategy as compared with the conservative strategy ($N = 12$, $p < .001$ uncorrected). Activation is overlaid on sagittal (upper left), coronal (upper right), and axial (lower left) slices. The color bar shows t values.

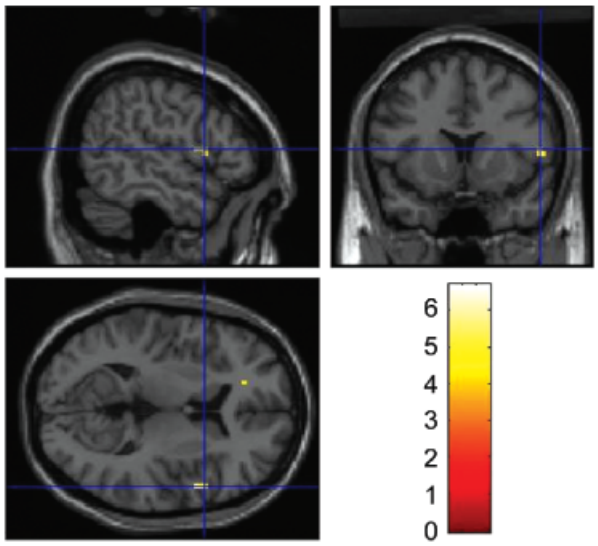

Fig. 4. Brain regions showing a significant interaction effect (greater psychological refractory period effect with the daring than with the conservative strategy, $N = 12$, $p < .001$ uncorrected). Activation is overlaid on sagittal (upper left), coronal (upper right), and axial (lower left) slices. The color bar shows t values.

DISCUSSION

We tested a large number of subjects in an effort to find neural correlates of the PRP. To our surprise, reducing the SOA between two choice RT tasks did not produce significant activation in regions important for executive functions, even though Task 2 was delayed considerably. If executive monitoring is necessary to coordinate between the two tasks during the short-SOA condition, we would expect to see increased activation in that condition in brain regions important for executive functions. However, none of the executive regions tested showed greater activation for the short- than the long-SOA condition. These regions, including DLPFC and ventrolateral PFC, ACC and pre-SMA, and the intraparietal sulcus, were clearly sensitive to some of the other experimental manipulations, such as choice versus simple RT, dual versus single tasks, and peripheral versus central attention. The delay in Task 2 RT produced by the PRP effect was considerably larger than the delay caused by these other manipulations, yet we found much less activation corresponding to the PRP effect. These findings suggest that the amount of increased central executive control during the short-SOA condition is relatively small and that PRP queuing is primarily passive.

A region in right GFi showed significantly greater activation during the short- than the long-SOA condition, but activation was negatively correlated with behavioral interference: The smaller the PRP effect, the larger the activation. An adjacent cluster (within 7 mm of peak distance) showed a greater SOA effect when subjects adopted a daring strategy than a conservative strategy, providing additional evidence that the reduced PRP effect in behavior was associated with increased activation in right GFi. Because the GFi activation was negatively, rather than positively, correlated with behavioral interference, we believe that it reflected increased mental effort devoted to the short-SOA task: The postponement of Task 2 itself was largely passive, although the attempt to reduce such postponement was active.

This study provides important constraints on theories of the PRP. The central-bottleneck theory (Pashler, 1994) postulates that the PRP reflects sequential queuing of two response selections. Although this theory does not preclude possible increases in additional processes during the PRP, it attributes the delay primarily to queuing the two tasks and is thus consistent with a passive-queuing account. The executive adaptive control (EAC) theory (Meyer & Kieras, 1997a, 1997b) rejects the existence of an immutable, structural central bottleneck. Instead, it proposes that subjects may strategically perform the two tasks sequentially to conform to task instructions. Dual-task interference arises because subjects need to monitor the progress of Task 1, halt Task 2, resume Task 2 after Task 1 is complete, and so on. Our fMRI data suggest that any such additional monitoring and control is minimal.

Will the present results generalize to all dual-task conditions? Perhaps not. Passive queuing may not be the primary strategy used to resolve all kinds of interference under all task conditions. In some situations, people can time-share between two tasks. Perception of up to four objects can occur concurrently (Pylyshyn & Storm, 1988), and perception of the second task can partially overlap with response selection of the first task (Pashler, 1984). In these cases, some behavioral interference typically persists, but subjects are not passively waiting for the completion of the first task. Thus, passive queuing may not be adopted in all dual-task situations.

CONCLUSIONS

Despite a very large RT cost for short-SOA compared with long-SOA conditions, we found no significant increase in brain activation for the short-SOA condition in regions postulated to be important for executive functions. This result is difficult to accommodate within a view that the short-SOA condition entails active monitoring. Instead, queuing of two response-selection tasks may be largely passive. It remains to be investigated how prevalent passive queuing is in other situations in which dual-task interference occurs.

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