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Resolving dual-task interference: an fMRI study

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The human cognitive system is severely limited in the amount of information it can process simultaneously. When two tasks are presented within a short stimulus-onset-asynchrony (SOA), reaction time of each task, especially task 2, is dramatically delayed. Previous studies have shown that such delay is accompanied by increased activation in the right inferior frontal gyrus (GFi). In this study, we address the role of right GFi in resolving dual-task interference at two different stages: allocation of perceptual attention and response selection. We scan 12 subjects using functional MRI while they conduct two tasks—shape discrimination in task 1 and color discrimination in task 2—and vary the SOA between tasks as 100 or 1500 ms. The targets are located at the center or at the periphery. When both are at the center, they compete primarily for response selection. When both are at the periphery, they additionally compete for the allocation of perceptual attention. Results show that the right GFi and frontal operculum regions are significantly more active in the short SOA than the long SOA condition, but only when subjects attend to the periphery in both tasks. We conclude that the right lateral frontal regions are important for resolving dual-task interference at the perceptual attention stage.

Keywords: fMRI; Dual-task interference; SOA

Introduction

One of the most fascinating aspects of human cognition is our ineffectiveness in conducting two tasks at the same time. Despite frequent wishes to divide attention between two tasks—such as turning left in traffic while carrying out a coherent conversation—most of us choose to stop performing one task until the other is complete. But what prevents one from responding to the traffic light at the same time as choosing the next sentence to say? Research in cognitive psychology has provided extensive evidence that human attention is limited in at least two respects: perceptual attention and response selection (Jiang and Kanwisher, 2003a).

Perceptual attention is used primarily to select targets and filter out distractors when multiple objects are presented. It can be simultaneously directed to approximately four visual objects. For example, in multiple-object tracking, subjects first see 10 dots, a few of them blinked initially, and then all dots move randomly on the screen. The subjects' ability to track the previously blinked dots is severely impaired if more than four dots are to be tracked (Pylyshyn and Storm, 1988).

Response selection also poses a cognitive limitation. Pashler (1984, 1994) proposes that there is a central cognitive bottleneck involved whenever a stimulus has to be mapped onto a response from an arbitrary rule, such as deciding to step on the brake when the traffic light turns red. Mapping a stimulus to a response—a decision process—precedes the execution of motor responses. Thus, while we can press a key and say a word at the same time (Pashler, 1993), we cannot simultaneously decide which key to press on the basis of a shape and decide which word to say on the basis of a tone.

Response selection is not only different from motor execution, but also separate from the allocation of perceptual attention. This is revealed in that the central bottleneck cannot be divided between two response selection processes, but perceptual attention can be divided between a few perceptual objects. Thus, when people encounter a competition for response selection, they hold the second task in a queue; but when they encounter a competition for perceptual attention, they divide a proportion of perceptual attention to each object. Therefore, perceptual attention can be simultaneously divided between up to four perceptual objects (Luck and Vogel, 1997; Pylyshyn and Storm, 1988), but response selection can only be sequentially allocated to one task at a time (Pashler, 1989, 1991).

In this study, we use functional MRI to investigate how the brain resolves dual-task interference at the stage of perceptual attention and the stage of response selection. Competition at a third stage—the motor response stage—has been addressed by a separate study by Herath et al. (2001) and will be discussed later. We use the "overlapping task" design adopted from behavioral studies on the central bottleneck (Pashler, 1984; Welford, 1952). In this design, two tasks are presented, separated by a variable stimulus-onset-asynchrony (SOA). When the SOA is short (e.g., 100 ms), the two tasks overlap in time and compete for perceptual attention and response selection. In this case, subjects have to perform task 1 AND task 2. As the SOA increases (e.g., to 1500 ms), the two tasks no longer overlap, so subjects only need to perform task 1 OR task 2. The difference between a short SOA condition ("AND") and a long SOA condition ("OR") reflects how the brain copes with overlapping stages of processing between two different tasks.

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Several previous neuroimaging studies have studied the effect of dual-task processing (e.g., Adcock et al., 2000; Bunge et al., 2000; D'Esposito et al., 1995; Klingberg, 1998; Koechlin et al., 1999). These studies compare blocks of concurrent processing of two tasks (e.g., sentence comprehension and mental rotation) with blocks of single tasks alone. They observe increased activation in the dual-task condition in the dorsolateral prefrontal cortex and other regions. This suggests that additional central executive control is needed to resolve the dual-task interference. However, two design properties make these studies nonideal for determining what goes on during overlapping processes. First, the dual-task condition uses a mixed-block design, which entails task-set switching between the two tasks (Allport and Wylie, 2000; Monsell and Driver, 2000). When a difference is found between a mixed-block and a single-task block, it may be attributed to either dual-task processing or task-set switching. Second, although the two tasks overlap in time in some studies, other studies have deliberately avoided overlapping processing. For example, in Klingberg's (1998) study, the two tasks in the dual-task block are scheduled apart by 1 s to avoid a competition in motor output, so the dual-task blocks actually involve the processing of "task 1 OR task 2". In the studies of D'Esposito et al., Adcock et al., and Bunge et al., although the two tasks are presented inside the same time window, each trial of one or both tasks is extended for several seconds. This may allow subjects to sequentially perform the two tasks (cf. Pashler, 1994). Thus, these studies have primarily examined the effect of maintaining two task sets and switching between them ("OR" vs. single tasks; see also Dove et al., 2000; Kimberg et al., 2000; Konishi et al., 1998; MacDonald et al., 2000; Rushworth et al., 2002), and have not isolated the effect of overlapping task processing per se ("AND" vs. "OR").

Four other studies have investigated the effect of overlapping tasks. Herath et al. (2001) present two tasks separated by either a short SOA (200–300 ms) or a long SOA (1150–1350 ms). One task is a simple visual RT task in which subjects press a key whenever an LCD is illuminated. The other task is a simple tactile RT task in which subjects press another key whenever they receive tactile stimulation. The choice of two different input modalities minimizes competition for perceptual processing (Pashler, 1998), and the choice of two simple RT tasks minimizes competition for response selection (Pashler, 1994). Herath et al. find increased activation in the right inferior frontal gyrus (GFi) in the short SOA compared with the long SOA condition. They suggest that the activation results from a competition for the same motor effector.

Szameitat et al. (2002) and Schubert and Szameitat (2003) test brain regions involved in tasks that overlap at a central stage. They use two choice-RT tasks that compete for the central bottleneck: a visual–motor and an auditory–motor task. Subjects are tested in a short SOA condition and blocks of single tasks. The short SOA condition shows increased activation in the right GFi compared with single tasks, suggesting that this region is involved not only in competition for the same motor effector (Herath et al., 2001), but also in competition for the central bottleneck. The interpretation of the studies of Szameitat et al. and Schubert and Szameitat is limited, however, by the omission of a long SOA condition. As noted earlier, the difference between a short SOA condition and single task blocks includes two components: resolving dual-task interference and switching task sets. It is unclear whether the right GFi activation is produced by the need to switch task sets in the short SOA condition, by competition for the central bottleneck, or both. In fact, when a long SOA condition is added in a recent fMRI study (Jiang et al., in press), the difference between the short SOA and the long SOA condition in the right GFi and other brain regions largely disappears, while the difference between the long SOA condition and single task blocks remains (Jiang et al., in press). This suggests that the right GFi may be more involved in task-set switching than in overlapping processing of response selection.

In this study, we further investigate the role of the right GFi in resolving dual-task interference at two different stages: perceptual attention and response selection. We hypothesize that GFi is activated whenever two processes proceed simultaneously, but not when they occur sequentially. We further hypothesize that simultaneous processing occurs when two perceptual processes or when two motor processes are separated by a short SOA, but not when two response selection processes are separated by a short SOA. As a result, the GFi will increase its activation when two tasks compete for the allocation of perceptual attention or for motor processing (Herath et al., 2001), but not when they compete for response selection. This study focuses on perceptual attention and response selection.

We test subjects in three task combinations: when subjects attend to the center target in both tasks, when they attend to the center target in task 1 and to the peripheral target in task 2, and when they attend to the peripheral target in both tasks.

On each display, subjects are presented with one central target, one peripheral target, and seven peripheral distractors. The items are geometric shapes in task 1 (square or circle as the targets and triangles as the distractors) and colors in task 2 (red or green as the targets and mixed colors as the distractors). Subjects are told to attend either to the central or to the peripheral targets and make responses to the target's shape in task 1 and to the target's color in task 2. Because the perception of a central target is easy, the competition involved in the center–center condition is primarily between the response selections of the two tasks. In the center–periphery condition, subjects have to shift attention from the center to the periphery. Finally, in the periphery–periphery condition, the two tasks compete not only for response selection but also for spatial attention to the periphery. Thus, while response selection is the main competition in the center–center condition, perceptual attention is an additional source for competition in the periphery–periphery condition. Will the neural substrates involved in resolving these two kinds of interference be different?

Method

Participants

Twelve healthy adults between 18 and 32 years old were tested. They all had normal or contact-corrected normal visual acuity and normal color vision. Subjects participated in a 30-min practice before scanning.

Tasks

Ten subjects completed six sessions of fMRI scans; the other two subjects completed two sessions. Each session included six task blocks composed of three task combinations and two SOAs. Each task block was preceded by a 14-s fixation and a 2-s instruction. The instruction informed subjects whether they should

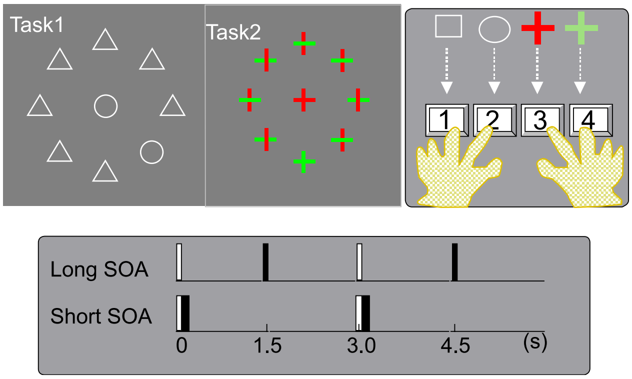

Fig. 1. Sample displays, response mapping, and trial sequence. In task 1, the central target and the peripheral target were either a square or a circle, chosen independently. The peripheral distractors were triangles. Subjects pressed '1' for a square and '2' for a circle. In task 2, the central and the peripheral targets were crosses of pure color—red or green. The peripheral distractors were crosses of mixed colors (one green segment and one red segment). Subjects pressed '3' for red and '4' for green. Subjects were told to attend to "central shape, central color", "central shape, peripheral color", or "peripheral shape, peripheral color" in different task blocks. Each display was presented for 100 ms. The SOA between the two displays was either 0.1 or 1.5 s (on the lower panel, white bars indicate the presentation of task 1 and black bars indicate the presentation of task 2).

attend to the center or to the periphery. Each task block lasted 48 s and included 16 task pairs presented at 3 s/pair. Each display contained one central target, one periphery target, and seven periphery distractors. The items in task 1 were geometric shapes. The distractors were triangles and the targets were square or circle. The items in task 2 were colored crosses. The distractors had mixed colors with one segment being red and the other segment being green. The targets were pure colors of either red or green. The peripheral target was chosen randomly from eight locations on an invisible circle (Radius = 3.3° for task 1, and 3.0° for task 2). Its identity could be the same or different from the central target. Fig. 1 shows a sample display.

The instruction informed subjects to attend to (1) the central shape and the central color; (2) the central shape and the peripheral color; or (3) the peripheral shape and the peripheral color. Subjects were asked to press '1' for a square and '2' for a circle, using their left hand, and to press '3' for red and '4' for green, using their right hand. Attention was tested in different blocks.

Each trial started with the presentation of the first task display for 0.1 s. After an interval of zero or 1.4 s, the second task display was presented for 0.1 s. The displays were presented briefly to discourage eye movements to the peripheral targets. Subjects were asked to respond as accurately and as quickly as possible to both tasks within a time-window of 3 s.

fMRI design

Subjects were tested in the Martinos imaging center in Charlestown, MA, on Siemens 3.0-T research scanners. We first collected 128 sagittal slices during the anatomical scans. During the functional scans, 28 contiguous axial slices (4 mm thick) were taken to cover the whole brain except the bottom half of the cerebellum (TR = 2 s, TE = 30 ms, flip angle = 90°). Each functional scan lasted 6 min 40 s, including six task blocks (48 s each) and seven fixation blocks (16 s each). The first six fixation blocks (each preceding a task block) were composed of 14 s of fixation and 2 s of instruction. The order of the six task blocks was counterbalanced.

fMRI data analysis

Using SPM99, we first preprocessed each subject's data, including motion correction, normalization to the MNI space, and spatial smoothing with a Gausian kernel (FWHM = 5 mm). Low frequency

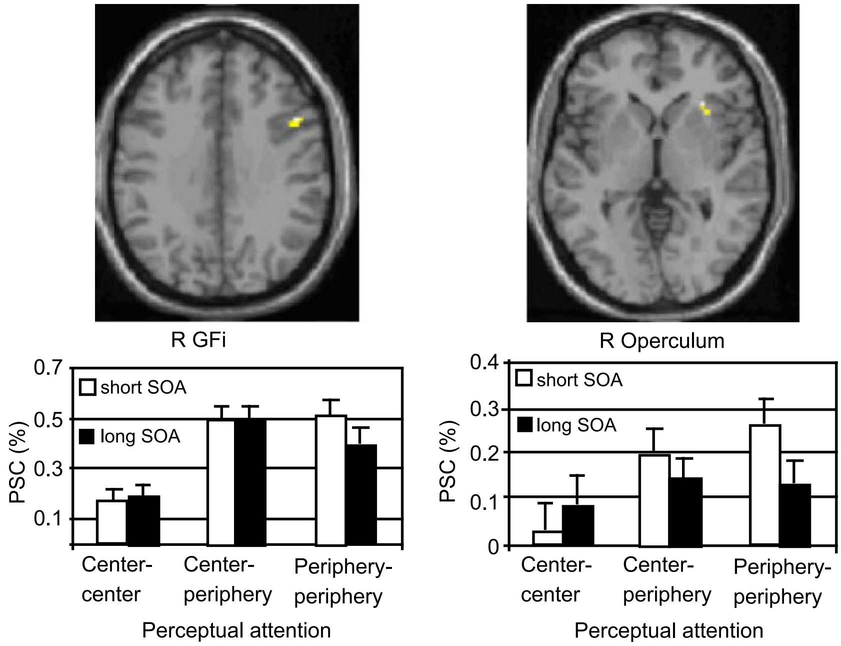

Fig. 2. Regions that were significantly more activated during the short than the long SOA conditions ($P < 0.001$, $N = 12$, random-effects analysis). GFi: inferior frontal gyrus. Error bars show standard error of the difference between the SOA conditions.

drifts were corrected in the analysis. Individual subjects' data were analyzed to test for "all task > fixation" and the main effect of "short SOA > long SOA". These contrast maps were then tested in a random-effect model for across subjects' consistency. Because of the small number of subjects, a threshold of $P < 0.001$ (extended to 5 voxels) uncorrected for multiple comparisons was used. Finally, based on the "task > fixation" contrast, we defined 15 functional regions-of-interest (ROI) including the parietal cortex, frontal eye fields, lateral prefrontal cortex, basal ganglia, occipital cortex, and cerebellum, and tested the percent signal change (PSC) in each task condition.

Results

Behavioral results

We calculated accuracy for all trials, RT for correct trials, and the correlation between task 1 and task 2's RT. Table 1 shows the results.

Presenting the two tasks within 100 ms of each other led to a dramatic increase in RT1 of about 200 ms and in RT2 of about 400 ms. An ANOVA on attention (center–center, center–periphery, periphery–periphery) and SOA (short vs. long) revealed significant main effects of attention and SOA in RT1 and RT2, P's < 0.0001. The interaction between attention and SOA was not significant for RT1, but was significant for RT2, $P < 0.001$. The SOA effect on RT2 was substantially larger when subjects attended to the peripheral targets (periphery–periphery, PRP = 491 ms) than when they attended to the central targets (center–center, PRP = 329 ms). This is consistent with the idea that the two tasks competed not only for response selection (which should be the same in all task combinations), but also for spatial attention when subjects attended to the periphery. Further evidence that task 2 was waiting for the completion of task 1 came from the correlation data between RT1 and RT2. The correlation coefficients were about 0.30 when the SOA was long, but jumped to around 0.80 when the SOA was short.

fMRI results

The effect of SOA

A random-effects analysis on the main effect of SOA (short SOA > long SOA, averaged across different task combinations) revealed two regions that showed an increased activation in the short SOA condition. The right inferior frontal gyrus (area 9, [48 15 33], 6 voxels) and the right frontal operculum (area 47, [30 24 0], 11 voxels) were significantly more active during the short than the long SOA conditions (Fig. 2).

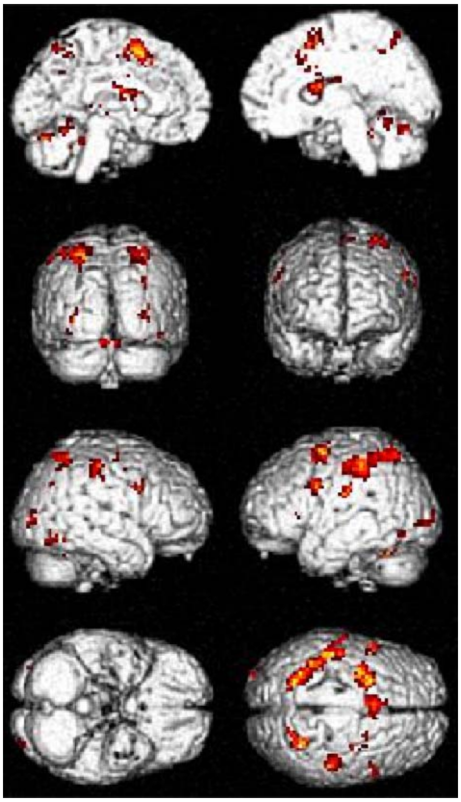

Fig. 3. Regions that showed task > fixation ($P < 0.001$ uncorrected, $N = 12$, random effects analysis).

To find out whether these two frontal regions showed a significant SOA effect in all task combinations, we calculated the percent signal change (PSC) in two regions-of-interest (ROIs) centered on the above locations (radius = 6 mm). This analysis showed that the SOA effect was primarily driven by a higher PSC for short than long SOA conditions when subjects attended to the periphery in both tasks. The SOA effect was significant in the periphery–

Table 1
Behavioral data collected during scanning

Attention	Center–center			Center–periphery			Periphery–periphery		
SOA	Short	Long	Interference	Short	Long	Interference	Short	Long	Interference
Accuracy1	0.99	0.97	−0.02, n.s.	0.94	0.92	−0.03, n.s.	0.92	0.94	0.02, n.s.
Accuracy2	0.95	0.95	0, n.s.	0.84	0.87	0.03, n.s.	0.88	0.91	0.03*
RT1 (ms)	805	570	235***	944	647	297***	1025	776	186***
RT2 (ms)	931	602	329***	1193	747	445***	1232	741	491***
r(RT1,RT2)	0.85	0.35	N/A	0.80	0.30	N/A	0.80	0.24	N/A
Difficulty rating[a]	4.73	3.86	*D* = 0.87, n.s.	8.25	6.18	*D* = 2.07**	8.37	6.83	*D* = 2.46**

n.s.: non-significant; N/A: not applicable.

[a] Subjects rated the difficulty of the tasks during practice on a scale from 1 to 10, where 1 was "very easy" and 10 was "very difficult".

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

Table 2
Percent signal change against the fixation baseline in task-related ROIs

ROI	MNI	Where	Center–center		Center–periphery		Periphery–Periphery	
		SOA	Short	Long	Short	Long	Short	Long
1	0 9 57	Pre-SMA	0.42	0.60*	0.62	0.70	0.69	0.66
2	−51 6 33	L GFi(44)	0.42	0.46	0.65	0.63	0.49	0.61
3	51 9 30	R GFi(44)	0.29	0.30	0.52	0.41	0.54	0.51
4	−27 −3 60	L FEF(6)	0.36	0.50	0.59	0.61	0.64	0.60
5	24 3 57	R FEF(6)	0.23	0.24	0.37	0.34	0.41	0.36
6	−18 −3 18	L Caudate	0.04	0.13	0.16	0.19	0.24	0.17
7	27 3 18	R Caudate	0.00	0.05	0.07	0.09	0.12	0.08
8	−45 −30 45	L aIPS(40)	0.35	0.41	0.47	0.49	0.51	0.46
9	42 −30 45	R aIPS(40)	0.29	0.24	0.38*	0.28	0.42*	0.30
10	−30 −54 51	L SPL(7)	0.42	0.50	0.66	0.68	0.74*	0.65
11	33 −54 54	R SPL(7)	0.41	0.35	0.69	0.61	0.77	0.65
12	−36 −72 −12	L GF(18)	0.18	0.25	0.26	0.31	0.36	0.30
13	39 −63 −12	R GF(18)	0.07	0.18	0.23	0.29	0.31	0.28
14	6 −66 −18	Cerebellum	0.13	0.24	0.25	0.35	0.35	0.32
15	−30 27 6	L GFi (45)	0.08	0.11	0.24	0.23	0.29	0.20

MNI: Montreal Neurological Institute brain atlas coordinate.
* $P < 0.05$ when comparing short SOA with long SOA.

periphery condition in both frontal regions ($P < 0.05$), but was not significant in the other two conditions ($P > 0.15$). The interaction between SOA and attentional condition was significant in the frontal operculum ($P < 0.05$) and was marginally significant in the GFi ($P < 0.08$).

Regions-of-interest analysis

To find out whether we had missed any other brain region involved in resolving the competition between two concurrent tasks, we used a regions-of-interest (ROI) approach to increase statistical power. We selected 15 additional brain regions that showed a significant effect of "task > fixation" ($P < 0.001$ uncorrected, random effects analysis). The ROIs were centered on the most significant voxel and included all task-related voxels ("task > Fixation") within a spherical volume of 9 mm of the peak voxel. Fig. 3 shows task-related activation and Table 2 shows the percent signal change above fixation in the 15 ROIs.

All ROIs showed a significant main effect of attention, with higher PSC when subjects attended to the periphery (center–periphery and periphery–periphery) than when they attended to the center. Only one region—right anterior IPS—showed a significant main effect of SOA, with higher PSC during the short than the long SOA conditions. The SOA effect was significant in the center–periphery and periphery–periphery conditions, but was not significant in the center–center condition.

It is interesting that the behavioral interference effect associated with SOA (about 400 ms) was numerically larger than that associated with allocating attention to the periphery (about 140 ms), yet many more brain regions were sensitive to spatial attention than to the competition induced by shortening the SOA.

Discussion

In this study, we confirm that a significant behavioral interference is observed when subjects have to perform two tasks overlapping in time. The duration of response to both tasks is dramatically increased (by about 200 ms in task 1 and about 400 ms in task 2). The interference is larger when both targets are in the periphery than when they are at the center. This suggests that in addition to competing for response selection, the two tasks compete for perceptual attention in the periphery–periphery condition. Results show a significant increase in activation in the right lateral prefrontal regions when the two tasks are presented within a short SOA rather than a long SOA. This activation is primarily driven by the periphery–periphery condition, suggesting that the right GFi is important for resolving interference at the level of perceptual attention.

The greater sensitivity of the right GFi to competition for perceptual attention than to competition for response selection is consistent with the idea that these two types of interference are resolved differently. Unlike response selection, perceptual attention is divisible and can be simultaneously allocated to two tasks (Pashler, 1989). On this account, subjects in the periphery–periphery, short SOA condition allocate perceptual attention to both targets simultaneously, although both tasks may be impaired because of the limited resources for perceptual attention. In contrast, when the two tasks compete mainly for response selection, as is the case in the center–center, short SOA condition, the interference is resolved primarily by holding task 2 in a queue. Because the working memory load produced by holding task 2 in a queue is minimum, the short and the long SOA conditions are essentially processed similarly. That is, in both conditions the two response selection processes are dealt with sequentially.

At first glance, the emphasis on the role of right GFi in resolving perceptual interference appears to be inconsistent with previous functions attributed to this region. Many studies have shown, for example, that the right GFi is involved in suppressing a prepotent response and in making a response selection (e.g., Bunge et al., 2002; Hazeltine et al., 2000; Jiang and Kanwisher, 2003a,b; Passingham et al., 2000; Sohn et al., 2000; Rubia et al., 2003). Few studies have ascribed a role of perceptual attention to the right GFi (Duncan and Owen, 2000). How should we reconcile the present result with other findings?

The answer to this question lies in that the current study is specifically about resolving overlapping task processing, while the other studies have focused on a given stage of process in single tasks. That is, we compared a short SOA condition with a long SOA condition, while other studies compared the presence with the absence of a certain cognitive process, such as inhibition of prepotent response. When subjects conduct a single task, which requires them to select a target among distractors, and to map the target onto an appropriate response, the right GFi is involved both during perceptual attention and during response selection (Jiang and Kanwisher, 2003a,b). The particular process tapped in the current study though is not about how perceptual attention or response selection is conducted, but about how the brain deals with overlapping task processes. Our finding is that the right GFi appears to be highly sensitive to overlapping perceptual attention processes and less so to overlapping response selections. This finding fits well with behavioral observations that perceptual attention can be divided between multiple objects, but response selection has to proceed sequentially. That is, presenting two tasks simultaneously changes how perceptual attention is allocated, but it does not change how response selection is conducted. When the SOA is long, both perceptual attention and response selection are allocated sequentially, whereas when the SOA is short, perceptual attention is allocated simultaneously and response selection remains sequential. In addition to perceptual attention, motor processing can be conducted in parallel (Pashler, 1994): one can simultaneously press a key and say a word, for example. Reducing the SOA between two tasks also potentially changes motor processes from sequential allocation to simultaneous allocation. Consistent with this analysis, Herath et al. found that the right GFi is involved in resolving interference at the level of motor process.

To conclude, we found that the inferior frontal gyrus, frontal operculum, and anterior IPS of the right hemisphere increase their level of activation when two tasks overlap in time. This is observed particularly when both tasks compete for perceptual attention. We suggest that in addition to their roles in response selection and perceptual attention of single tasks, the right ventral prefrontal regions are involved when attention has to be simultaneously divided between two perceptual attention processes.

Acknowledgments

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References

Adcock, R.A., Constable, R.T., Gore, J.C., Goldman-Rakic, P.S., 2000. Functional neuroanatomy of executive processes involved in dual-task performance. Proc. Natl. Acad. Sci. U. S. A. 28, 3567–3572.

Allport, A., Wylie, G., 2000. Task switching, stimulus-response bindings, and negative priming. In: Monsell, S., Driver, J. (Eds.), Attention and performance. Control of Cognitive Processes, vol. XIIIV. MIT Press, Cambridge, MA, pp. 35–70.

Bunge, S.A., Klingberg, T., Jacobsen, R.B., Gabrieli, J.D., 2000. A resource model of the neural basis of executive working memory. Proc. Natl. Acad. Sci. U. S. A. 28, 3573–3578.

Bunge, S.A., Hazeltine, E., Scanlon, M.D., Rosen, A.C., Gabrieli, J.D., 2002. Dissociable contributions of prefrontal and parietal cortices to response selection. NeuroImage 17, 1562–1571.

D'Esposito, M., Detre, J.A., Alsop, D.C., Shin, R.K., Atlas, S., Grossman, M., 1995. The neural basis of the central executive system of working memory. Nature 378, 279–281.

Dove, A., Pollmann, S., Schubert, T., Wiggins, C.J., von Cramon, D.Y., 2000. Prefrontal cortex activation in task switching: an event-related fMRI study. Cognit. Brain Res. 9, 103–109.

Duncan, J., Owen, A.M., 2000. Common regions of the human frontal lobe recruited by diverse cognitive demands. Trends Neurosci. 23, 475–483.

Hazeltine, E., Poldrack, R., Gabrieli, J.D., 2000. Neural activation during response competition. J. Cogn. Neurosci. 12, 118–129.

Herath, P., Klingberg, T., Yong, J., Amunts, K., Roland, P., 2001. Neural correlates of dual task interference can be dissociated from those of divided attention: an fMRI study. Cereb. Cortex 11, 796–805.

Jiang, Y., Kanwisher, N., 2003a. Common neural mechanisms for response selection and perceptual processing. J. Cogn. Neurosci. 15 (8), 1095–1110.

Jiang, Y., Kanwisher, N., 2003b. Common neural substrates for response selection across modalities and mapping paradigms. J. Cogn. Neurosci. 15 (8), 1077–1079.

Jiang, Y., Saxe, R., Kanwisher, N., in press. FMRI provides new constraints on theories of the Psychological Refractory Period. Psychol. Sci.

Kimberg, D.Y., Aguirre, G.K., D'Esposito, M., 2000. Modulation of task-related neural activity in task-switching: an fMRI study. Cognit. Brain Res. 10, 189–196.

Klingberg, T., 1998. Concurrent performance of two working memory tasks: potential mechanisms of interference. Cereb. Cortex 8, 593–601.

Koechlin, E., Basso, G., Pietrini, P., Panzer, S., Grafman, J., 1999. The role of the anterior prefrontal cortex in human cognition. Nature 399, 148–151.

Konishi, S., Nakajima, K., Uchida, I., Kameyama, M., Nakahara, K., Sekihara, K., Miyashita, Y., 1998. Transient activation of inferior prefrontal cortex during cognitive set shifting. Nat. Neurosci. 1, 80–84.

Luck, S.J., Vogel, E.K., 1997. The capacity of visual working memory for features and conjunctions. Nature 390, 279–281.

MacDonald III, A.W., Cohen, J.D., Stenger, V.A., Carter, C.S., 2000. Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science 288, 1835–1838.

Monsell, S., Driver, J., 2000. Attention and performance. Control of Cognitive Processes, vol. XIIIV. MIT Press, Cambridge, MA, pp. 3–32.

Pashler, H., 1984. Processing stages in overlapping tasks: evidence for a central bottleneck. J. Exp. Psychol. Hum. Percept. Perform. 10, 358–377.

Pashler, H., 1989. Dissociations and dependencies between speed and accuracy: evidence for a two-component theory of divided attention in simple tasks. Cognit. Psychol. 21, 469–514.

Pashler, H., 1991. Shifting visual attention and selecting motor responses: distinct attentional mechanisms. J. Exp. Psychol. Hum. Percept. Perform. 17, 1023–1040.

Pashler, H., 1993. Doing two things at the same time. Am. Sci., 47–56.

Pashler, H., 1994. Dual-task interference in simple tasks: data and theory. Psychol. Bull. 116, 220–244.

Pashler, H., 1998. The psychology of attention. MIT Press, Cambridge, MA.

Passingham, R.E., Toni, I., Rushworth, M.F., 2000. Specialization within the prefrontal cortex: the ventral prefrontal cortex and associative learning. Exp. Brain Res. 113, 103–113.

Pylyshyn, Z.W., Storm, R.W., 1988. Tracking multiple independent targets: evidence for a parallel tracking mechanism. Spat. Vis. 3, 179–197.

Rubia, K., Smith, A.B., Brammer, M.J., Taylor, E., 2003. Right inferior prefrontal cortex mediates response inhibition while mesial prefrontal cortex is responsible for error detection. NeuroImage 20, 351–358.

Rushworth, M.F.S., Hadland, K.A., Paus, T., Sipila, P.K., 2002. Role of the human medial frontal cortex in task switching: a combined fMRI and TMS study. J. Neurophysiol. 87, 2577–2592.

Schubert, T., Szameitat, A.J., 2003. Functional neuroanatomy of interference in overlapping dual tasks: an fMRI study. Cognit. Brain Res. 17, 733–746.

Sohn, M.H., Ursu, S., Anderson, J.R., Stenger, V.A., Carter, C.S., 2000. The role of prefrontal cortex and posterior parietal cortex in task switching. Proc. Natl. Acad. Sci. U. S. A. 97, 13448–13453.

Szameitat, A.J., Schubert, T., Muller, K., von Cramon, D.Y., 2002. Localization of executive functions in dual-task performance with fMRI. J. Cogn. Neurosci. 14, 1184–1199.

Welford, A.T., 1952. The "psychological refractory period" and the timing of high speed performance—A review and a theory. Br. J. Psychol. 43, 2–19.