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The neural effect of stimulus-response modality compatibility on dual-task performance: an fMRI study

Abstract Recent fMRI studies suggest that the inferior frontal sulcus (IFS) is involved in the coordination of interfering processes in dual-task situations. The present study aims to further specify this assumption by investigating whether the compatibility between stimulus and response modalities modulates dual-task-related activity along the IFS. It has been shown behaviorally that the degree of interference, as measured by dual-task costs, increases in modality-incompatible conditions (e.g. visual–vocal tasks combined with auditory–manual tasks) as compared to modality-compatible conditions (e.g. visual–manual tasks combined with auditory–vocal tasks). Using fMRI, we measured IFS activity when participants performed modality-compatible and modality-incompatible single and dual tasks. Behaviorally, we replicated the finding of higher dual-task costs for modality-incompatible tasks compared to modality-compatible tasks. The fMRI data revealed higher activity along the IFS in modality-incompatible dual tasks compared with modality-compatible dual tasks when inter-individual variability in functional brain organization is taken into account. We argue that in addition to temporal order coordination (Szameitat et al., 2002), the IFS is involved in the coordination of cognitive processes associated with the concurrent mapping of sensory information onto corresponding motor responses in dual-task situations.

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Introduction

Concurrent processing of information frequently interferes with information processing relevant to goal-directed behavior. In order to reach our goals despite this interference we must coordinate the concurrent information-processing streams according to our internal goal hierarchy. The question of how this fundamental regulation of behavior happens and how this is realized by the human brain has been addressed in a number of recent studies using functional magnetic resonance imaging (fMRI).

Many of these studies used experimental paradigms requiring the suppression of prepotent response tendencies, which compete with the required responses in single-task situations (e.g. Bunge, Hazeltine, Scanlon, Rosen & Gabrieli, 2002; Dove, Pollmann, Schubert, Wiggins & von Cramon, 2000; Fan, Flombaum, McCandliss, Thomas & Posner, 2003; Iacoboni, Woods & Mazziotta, 1996; Jiang & Kanwisher, 2003; MacDonald, Cohen, Stenger & Carter, 2000; Milham, Banich, Webb, Barad, Cohen & Wszalek, 2001; Schumacher, Elston & D'Esposito, 2003; Schumacher & D'Esposito, 2002; Thompson-Schill, D'Esposito, Aguirre & Farah, 1997; Zysset, Müller, Lohman & von Cramon, 2001). Despite the fact that most of these studies found activation in multiple brain regions, the activation associated with the coordination of interfering task processes that was observed in regions surrounding the inferior frontal sulcus (IFS) was one of the most consistent.

Interfering task processes also occur in dual-task situations where we must coordinate the processing streams of two independent tasks (DeJong, 1995; Meyer & Kieras, 1997). Recent fMRI research suggests that coordination of interfering task processes in dual-task situations is also associated with increased activity in the IFS (Schubert & Szameitat, 2003; Szameitat, Schubert, Müller & von Cramon, 2002). Using simple choice-reaction tasks, these studies further specified findings of

earlier studies about the role of the lateral prefrontal cortex in dual-task situations (e.g. D'Esposito, Detre, Alsop, Shin, Atlas, & Grossmann, 1995; Koechlin, Basso, Pietrini, Panzer & Grafman, 1999). However, the precise cognitive mechanisms associated with the dual-task-related IFS activation are still undetermined.

In order to specify these cognitive mechanisms, it is important to disentangle different factors that may modulate specific aspects of dual-task coordination. By investigating which factors affect the activity within the IFS, inferences can be made about the role of the IFS as a neural substrate for the manipulated cognitive function (Braver, Cohen, Nystrom, Jonides, Smith, & Noll, 1997).

Following this logic, Szameitat et al. (2002) parametrically manipulated one aspect of dual-task coordination, namely the extent to which the temporal order of the two tasks has to be coordinated. They used the dual-task procedure of the psychological refractory period (PRP; Pashler, 1994) and presented dual-task blocks with the two tasks having a fixed presentation order and blocks with the two tasks having random presentation order. Within random-order blocks, the task processes must be rearranged whenever the presentation order of the tasks changes (DeJong, 1995; Meyer, Kieras, Lauber, Schumacher, Glass, Zubriggen, Gmeindl, & Apfelblat, 1995). As a consequence, temporal order coordination is more demanding here compared with that in fixed-presentation-order blocks. As shown by the subsequent parametric analysis of the fMRI data, in the IFS, a higher activity was found for the random-order condition compared with the fixed-order condition. On the basis of these findings Szameitat et al. concluded that the IFS is associated with coordinating the temporal order of two interfering processing streams in dual-task situations (see also Szameitat, Schubert, Lepsien, von Cramon & Sterr, 2005).

However, manipulating dual-task coordination by varying the task presentation order, as proposed by Szameitat et al. (2002), may represent only one type of manipulation leading to increased dual-task-related IFS activation—other factors related to different aspects of coordination might affect the amount of IFS activation in dual tasks as well. An analysis of the influence of such additional factors on dual-task-related IFS activation is necessary in order to further specify the precise role of the IFS in dual-task processing.

In the present study, we investigated the influence of the compatibility between stimulus and response modalities in component tasks on dual-task-related IFS activation. Recent behavioral studies (E. Hazeltine, E. Ruthruff & R. W. Remington, under review; Levy & Pashler, 2001) suggest that modality compatibility is one factor that affects dual-task performance. Other factors include the amount of temporal overlap of the component tasks (Welford, 1952; Pashler, 1994), the amount of dual-task practice (Schumacher, Lauber, Glass, Zurbriggen, Gmeindl, Kieras, & Meyer, 1999; Schumacher, Seymour, Glass, Fencsik, Lauber, Kieras, & Meyer, 2001; van Selst, Ruthruff & Johnston, 1999), or the degree of cross-task compatibility (Hommel, 1998; Koch & Prinz, 2002; Logan & Schulkind, 2000).

Modality compatibility and the present study

Based on findings from single-task studies (e.g. Greenwald, 1970; Virzi & Egeth, 1985; Wang & Proctor, 1996), stimulus–response pairs can be classified as modality-compatible (e.g. visual–manual, auditory–vocal) and modality-incompatible (e.g. visual–vocal, auditory–manual). Hazeltine and colleagues compared dual tasks consisting of modality-compatible tasks (i.e., visual–manual and auditory–vocal) with dual tasks consisting of modality-incompatible tasks (i.e., visual–vocal and auditory–manual). Significantly higher dual-task costs were found for modality-incompatible conditions compared with modality-compatible conditions. Interestingly, the increase of dual-task costs in modality-incompatible conditions could not be explained solely by differences in the difficulty of the component tasks. Taken together, these findings suggest that interference in dual-task situations is determined in part by the modality compatibility of the component tasks, which changes processes associated with the mapping between stimulus codes and response codes. In dual-task conditions where two mapping processes have to be performed concurrently, this leads to increased coordination demands in modality-incompatible situations compared with modality-compatible ones.

Our current study investigates whether modality-incompatible dual tasks evoke increased fMRI activity in dual-task-specific IFS regions, as compared to modality-compatible dual tasks. If so, this would substantially augment the findings of Szameitat et al. (2002). It would suggest that, in addition to being involved in the coordination of temporal order, the IFS is involved in the coordination of cognitive processes associated with the concurrent mapping of sensory information onto corresponding motor responses in a dual-task situation.

In the present study, participants performed single and dual tasks in a blocked fMRI design. The specific pairings of stimuli and responses created modality-compatible (e.g., visual–manual and auditory–vocal) and modality-incompatible (e.g., visual–vocal and auditory–manual) single and dual tasks. In this way, we were able to determine dual-task-specific activity by comparing single and dual tasks and to test whether IFS activity varies with additional coordination demands in the direct comparison of the two dual tasks. To our knowledge, this is the first fMRI study that uses different stimulus and different response modalities of the component single tasks in a dual-task situation. Therefore, the finding of dual-task-specific activity in the lateral prefrontal cortex would

allow generalizing the results of previous studies, which showed dual-task-specific activity in this region using overlapping input and/or output modalities.

Investigating dual-task-related activity by combined individual and group analyses

In most studies investigating the functional neuro-anatomy of cognitive processes in the prefrontal cortex, activity patterns are summarized across participants to show the general involvement of these regions in specific processes. However, the anatomical and functional organization of frontal, particularly, prefrontal areas, is known to be highly variable across individuals (D'Esposito, Ballard, Aguirre & Zarahn, 1998; Miller, van Horn, Wolford, Handy, Valsangkar-Smyth, Inati, Grafton, & Gazzaniga, 2002; Rajkowska & Goldman Rakic, 1995). For example, D'Esposito et al. (1998) investigated prefrontal activity in a working memory task by analyzing the individual activation peaks of participants. An analysis of the activation data showed the high interindividual variability in the exact localization of prefrontal activation peaks. Similarly, Miller et al. (2002) showed the consistency of individual brain activity patterns over time, despite the extensive variability between individuals, in an episodic memory task. Both studies show that combining individual and group analyses is important in order to fully understand the neural implementation of higher cognitive functions.

Because the IFS was already identified by Szameitat et al. (2002) as a relevant structure for dual-task coordination, we compared the amount of activation between modality-compatible and modality-incompatible dual tasks in the individual dual-task-specific regions along the IFS. By using an approach like this, interindividual variability in functional organization can be taken into account. At the same time, we will perform a statistical comparison of the signal changes in different conditions at the level of group-averages. The combination of these two methods of data analysis allows us to get more detailed information about the real location of individual dual-task-related areas, while preserving the statistical conservatism of a group-based analysis of the data.

Methods

Participants

Thirteen healthy right-handed volunteers with normal or corrected-to-normal vision participated in the experiment. Three were excluded from analysis due to high head-movement parameters or technical failure. Ten participants were analyzed (8 females, ages 21–28). All participants were recruited from the University of California community and gave their informed consent.

Behavioral procedure

Visual and auditory stimuli were presented using E-prime presentation software (http://www.pstnet.com). Visual stimuli and instructions were projected onto a screen that the participants viewed through a mirror mounted on the head of the radio-frequency (RF) coil while lying in the fMRI Scanner. Auditory stimuli were presented via headphones (http://www.avotec.org). Participants performed manual responses using a response box positioned on their abdomens. The buttons on the box were arranged so that the left button was closer to the participants' heads and the right button closer to the feet, so that the button presses had a left–right and a high–low dimension. This ensured similar spatial relations between response buttons and stimulus dimensions when participants performed left–right and high–low manual finger responses (see below).

Vocal responses were recorded using a microphone attached inside a SCUBA mouthpiece that the participants wore over their mouths. The mouthpiece filtered the gradient noise so that the vocal responses could be successfully recorded and analyzed. Task and fixation conditions were presented block-wise. An instruction screen preceded each block. Participants performed four types of single tasks and two types of dual tasks (see Fig. 1).

Modality-compatible tasks

Visual–manual single task (SINGLE-VM) A trial in the SINGLE-VM task began with a centrally presented fixation stimulus (+) for 200 ms. A pre-stimulus display followed the fixation stimulus for 400 ms. This display consisted of two white circles on a black background on each side of the fixation stimulus. The stimulus display roughly subtended 1.5° horizontally and 1.1° vertically. Next, a white disk (the cue stimulus) replaced one of the
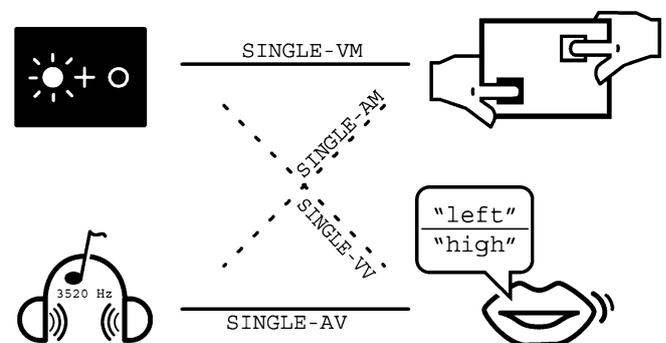
Fig. 1 Modality compatible (*solid lines*) and modality incompatible (*dashed lines*) stimulus–response pairs. *SINGLE-VM* single task visual–manual; *SINGLE-AV* single task auditory–vocal; *SINGLE-AM* single task auditory-manual; *SINGLE-VV* single task visual–vocal. SINGLE-VM and SINGLE-AV were performed simultaneously in the modality compatible dual task (*DUAL-COMP*), SINGLE-AM and SINGLE-VV were performed simultaneously in the modality incompatible dual task (*DUAL-INCOMP*)

circles for 200 ms. The post-stimulus display, which was identical to the pre-stimulus display, followed the cue stimulus for 1,400 ms. During this time, participants had to respond to the location of the cue stimulus by pressing the left button with their left index fingers for a stimulus that appeared on the left side of the fixation cross and the right button with their right index fingers for a stimulus on the right side.

Auditory–vocal single task (SINGLE-AV) A trial in the SINGLE-AV task began identically to the SINGLE-VM task, with a 200 ms fixation period, followed by the pre-stimulus display for 400 ms. Now, instead of a white disk, a tone frequency either 220 or 3,520 Hz was presented binaurally for 200 ms. During the post-stimulus display participants responded by saying "low" for the low-frequency tone and "high" for the high-frequency tone.

Modality-compatible dual task (DUAL-COMP) In the DUAL-COMP task, the SINGLE-VM and the SINGLE-AV tasks were performed together. The visual and auditory stimuli were presented simultaneously (SOA = 0) and the timing of the trials was just as in the single tasks. Participants were instructed to give their manual responses first and then speak loudly and clearly into the microphone, while trying to be as fast and correct as in the single tasks. Our pilot studies indicated that most participants responded manually first, even when no such instruction was given.

Modality-incompatible tasks

Visual–vocal single task (SINGLE-VV) Stimulus presentation and timing of the trials were the same as in the SINGLE-VM task. However, instead of a button press, now participants made the vocal responses "left" and "right" for the left and right cue stimuli, respectively.

Auditory–manual single task (SINGLE-AM) Stimulus presentation and timing of the trials were the same as in the SINGLE-AV task. During the post-stimulus display, participants pressed a button with their left index fingers on the high tone and with their right index fingers on the low tone. Note that participants in pilot studies rated this kind of mapping highly compatible when lying on their back instead of sitting upright.

Modality-incompatible dual tasks (DUAL-INCOMP) In the modality incompatible dual task, the SINGLE-VV and the SINGLE-AM tasks were performed together. As in DUAL-COMP, the visual and auditory stimuli were presented simultaneously (SOA = 0) and participants were instructed to give their manual responses first. Note that, because of the pre-defined response order, it cannot be excluded that performance differences in the vocal tasks are triggered by

dual-task effects in the manual tasks only. This should be subject to further experiments but in our view does not restrict the conclusions concerning the present data set.

Fixation (FIX) Additionally, we included a fixation condition in which the participants were instructed to fixate a centrally presented fixation cross, in order to get a baseline measure of brain activation.

Design of measurement Each fMRI block consisted of twelve task trials. The duration of each block was 26.4 s. An instruction screen was presented for 4.4 s before the beginning of each block. Each block was presented twice per run. Each fMRI run lasted 7:11 min (196 scans). We collected eight runs for each participant. The presentation order of the blocks was counterbalanced across participants, with the restriction that the three modality-compatible conditions (DUAL-COMP, SINGLE-VM, SINGLE-AV) and the three modality-incompatible conditions (DUAL-IN-COMP, SINGLE-VV, SINGLE-AM) were always presented as a sequence. The order of the sequence was also counterbalanced between participants. Participants performed two training sessions outside the scanner in the 2 days before scanning. The first session familiarized the participants with the different S–R mappings; the second session served as preparation for the session in the MR scanner. By the end of session 2, participants had performed each single task on 360 trials and each dual task on 432 trials. Also, participants were given the information that the top three performers, based on their reaction times (RTs) and their error rates, would receive an extra bonus of $20. Every participant was paid $10 an hour.

fMRI procedure

All images were acquired using a 4 T Varian INOVA MR scanner (http://www.varianinc.com) equipped with a fast gradient system for echo-planar imaging. A standard RF head coil with foam padding was used in order to restrict head motion, comfortably. Functional images were acquired using a two-shot gradient-echo, echo-planar sequence (TR = 2,200 ms, TE = 28 ms, matrix size = 64×64, FOV = 22.4 cm, flip angle = 20°). Each functional volume consisted of 20 3.5-mm axial slices with gaps of 0.5 mm. Two structural T1-weighted scans were also acquired. Before the functional imaging, 20 axial slices that were in-plane with the functional data were acquired using a gradient-echo multislice sequence (TR = 200 ms, TE = 5 ms, matrix size = 256×256, FOV = 22.4 cm). At the end of the session, a high-resolution 3-D MP-Flash scan (TR = 9 ms, TE = 4.8 ms, TI = 300 ms) was collected, which was used for normalization to the Montreal Neurological Institute (MNI) atlas space.

fMRI data analyses

First, the functional data from k-space were reconstructed and the image volumes corrected for slice-timing skew. All further analyses were carried out with SPM2 (http://www.fil.ion.ucl.ac.uk/spm/spm2.html). Each participant's functional data set was motion-corrected and spatially normalized into the standard MNI atlas space. Then, the data were smoothened with an 8-mm FWMH Gaussian kernel and were high-pass filtered during analysis.

Group analysis of fMRI data

In the first step, the group data was tested for dual-task-specific activity in order to determine whether the dual tasks used in this study also evoked additional activity in lateral frontal cortices as compared to the component single tasks.

The analysis was carried out using the general linear model for serially autocorrelated data implemented in SPM2 (Friston, Holmes, Worsley, Poline, Frith, & Frackowiak, 1995). For each individual participant, statistical parametrical maps (SPMs) were created. To test for dual-task-specific activity, the logic of the interaction contrast, described by Szameitat et al. (2002), applied to all six tasks was used. This resulted in the following contrast: [(DUAL-COMP − FIX) + (DUAL-INCOMP − FIX)] − [(SINGLE-VM − FIX) + (SINGLE-AV − FIX) + (SINLGE-VV − FIX) + (SINGLE- AM − FIX)]. For the group analysis, individual SPMs were averaged and voxelwise one-sample t-tests were performed on these averaged images. To correct for multiple comparisons we used a threshold of $P < 0.05$, corrected with False Discovery Rate as implemented in SPM2 (Genovese, Lazar, & Nichols, 2003).

Individual regions-of-interest (ROI) analysis

In the second step, an ROI approach was used in order to compare the blood-oxygen-level-dependent (BOLD) signal changes in the two types of dual tasks, along the IFS. We performed two types of ROI analyses—one using an ROI based on the location of the group peak activation along the IFS and another approach using ROIs based on the individual peak activations along the IFS. The latter method is more sensitive to smaller activity changes. This is because only regions that are most activated in each participant are used for ROI definition, instead of using a region that is just commonly activated across all participants. Differences in individual anatomy and in the gradation of the expected activation along the IFS may decrease the signal-to-noise ratio in ROIs that are determined on the basis of group activation as compared to an analysis based on individual activations.

For the ROI analyses, the IFS was masked with an ROI mask drawn in MRIcro (http://www.cla.sc.edu/psyc/faculty/rorden/mricro.html) and the group peak voxels and the individual peak voxels were determined within this area for the dual task minus single task contrast using the WFU-PickAtlas tool (http://www.fmri.wfubmc.edu). To make sure that the peaks that were determined in MNI space fell into the individual participant's structure of interest, the location of the peak voxels were checked in the brains of each individual in native space. If the peak activation fell outside the IFS in native space, the next highest activation which fell into the IFS was used – this was done for one participant (no 8). Around these peak voxels, a spherical mask with a radius of 4 mm (~33 voxels) was applied using MarsBaR (http://marsbar.sourceforge.net). From these masked regions, we extracted the mean β-values for all six conditions, individually, for each participant. The β-values are used as a measure of neural activity and indicate the direction and the size of the relationship between the design matrix and the BOLD signal changes. An ANOVA with repeated measures and subsequent one-tailed paired t-tests were performed to compare the β-values in the different task conditions.

Results

Behavioral data

Mean RTs and accuracies for the single and dual tasks are shown in Fig. 2. The statistical results for averaged reaction times and error rates across the two modality-compatible and modality-incompatible single and dual tasks are reported (but see Table 1 for the performance data of all tasks separately). That way, all data points stem from two tasks with exactly the same visual and auditory stimuli and the same manual and vocal responses, only differing in the two factors of interest, task type (single vs dual task) and modality compatibility. An ANOVA with repeated measures (factors modality compatibility and task type) was performed across mean RTs. It revealed a reliable effect of modality compatibility on mean RTs, $F(1,9) = 46.89$, MSE = 2157.98, $P < 0.001$. That is, averaged over single and dual tasks, the RTs in modality-incompatible tasks were slower than in modality-compatible tasks. The significant interaction between task type and modality compatibility, $F(1,9) = 66.98$, MSE = 1654.98, $P < 0.001$, indicates that RTs were increased in modality-incompatible conditions compared with modality-compatible ones only in dual-task situations, $t(9) = 7.68$, $P < 0.001$, and not in single-task situations, $t(9) = 0.70$, $P = 0.50$. In addition, the RTs were generally increased in dual-task situations compared to single-task ones, $F(1,9) = 111.23$, MSE = 4152.95, $P < 0.001$, indicating the emergence of dual-task costs. Consequently, the amount of these dual-task costs increased significantly in the modality-incompatible condition compared with the modality-compatible condition, $t(9) = 8.18$, $P < 0.001$.

Fig. 2 Behavioral data. RTs and error rates averaged for the modality compatible and modality incompatible tasks. *Left axis and filled bars* depict the RTs, *right axis and striped bars* depict the error rates. *Error bars* denote the standard error
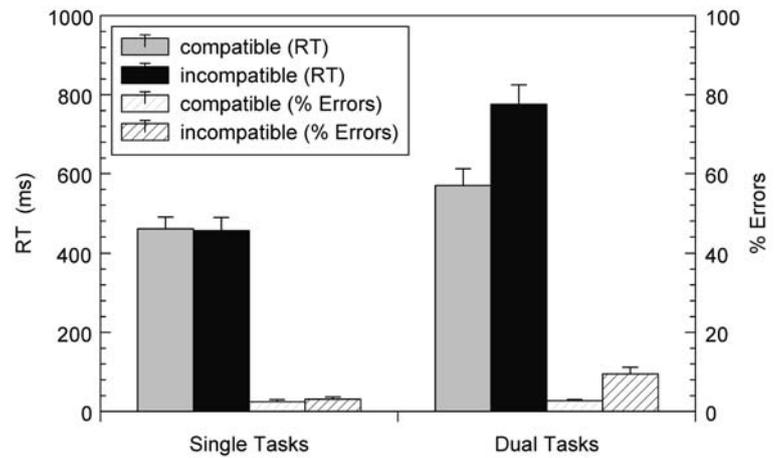
Table 1 Behavioral data

	Single tasks RT (ms) %Errors		Dual tasks RT (ms) %Errors	
Compatible				
Visual–manual	440.9	3.1	527.6	2.1
Auditory–vocal	479.7	1.9	612.3	3.3
Incompatible				
Auditory–manual	527.6	4.3	681.5	14.1
Visual–vocal[a]	366.5	1.8	870.1	4.9

Mean reaction times (RT) and error rates averaged for all tasks
[a]Note. In pilot studies outside the scanner, subjects responded faster on the auditory–manual single task than on the visual–vocal single task

An ANOVA with repeated measures (factors modality compatibility and task type) on the error rates confirmed the findings of the RT analysis. Participants made more errors in modality-incompatible tasks compared with modality-compatible ones, $F(1,9) = 22.49$, MSE $= 0.0006$, $P = 0.001$. However, as indicated by the significant interaction of modality compatibility and task type, $F(1,9) = 9.57$, MSE $= 0.001$, $P < 0.05$, this holds true for dual-task situations, $t(9) = 3.99$, $P < 0.01$, but not for single-task situations, $t(9) = 1.09$, $P > 0.2$. Additionally, the error rates were increased in dual-task situations compared with single-task ones, $F(1,9) = 10.79$, MSE $= 0.001$, $P < 0.01$, confirming the findings of the RT analysis. However, dual-task costs were significant for the modality-incompatible condition, $t(9) = 3.32$, $P > 0.01$, but not for the modality-compatible condition.

fMRI data Group analysis

First, we investigated whether there was dual-task-specific activity in the group activation map. Therefore, whole-brain voxel-wise t-tests were carried out on the dual-task minus single-task contrast as described in the Methods section. The results of this analysis are shown in Table 2.

The dual-task minus single-task contrast revealed dual-task-specific activations predominantly in prefrontal and parietal cortices. The lateral prefrontal activation foci were located in cortical regions surrounding the left IFS, in regions surrounding bilaterally the posterior parts of the superior frontal sulcus (SFS) and the precentral sulcus. Activations in medial frontal cortex were located bilaterally along the rostral part of the cingulate sulcus (ACC) and in the left presupplementary area. Activations in parietal regions were located bilaterally along the intraparietal sulcus, the precueneus and the lateral inferior parietal lobe—activations were more pronounced in the left hemisphere. In addition, we found dual-task-related activation in the left superior temporal gyrus, the right pallidum, and the left cerebellum.

Individual ROI analysis

The ROI analysis was restricted to activation peaks located along the left IFS, because no reliable dual-task-specific group activations were found in regions surrounding the right IFS. The ROI analysis based on the group peak activation in regions surrounding the left IFS (−38, 36, 22) did not reveal any significant dif-

Table 2 Stereotactic coordinates (Talairach & Tournoux, 1988) and anatomical location of peak activations in dual-task-related regions in the group analysis

Anatomical area	Hem	BA	Talairach coordinates			t value	P value (FDR corr)
			x	y	z		
Frontal							
IFS	L	46	−38	36	22	5.47	0.024
Precentral S	L	6	−30	−5	46	11.18	0.006
SFS	L	6	−30	3	53	7.6	0.014
SFS	R	6	30	−1	55	8.98	0.011
Precentral S	R	6	38	0	46	5.49	0.024
Precentral S	R	6	44	0	39	4.67	0.032
Pre-SMA	L	6	−10	7	57	8.12	0.013
ACC	L	6/32	−8	14	42	7.66	0.014
Cingulate S/G	L	32	−10	19	32	5.34	0.025
Cingulate S/G	R	32	12	21	30	5.39	0.025
Parietal							
Sup. Parietal lobe(IPS)	L	7	−20	−56	45	18.08	0.002
Inf. Parietallobe	L	40	−36	−48	47	10.62	0.006
Precuneus	L	7	−14	−68	42	12.77	0.005
Sup. Parietal lobe(IPS)	R	7	20	−60	49	5.32	0.026
Inf. Parietal lobe(IPS)	R	40	38	−38	48	5.33	0.026
Precuneus	R	7	22	−62	40	5.6	0.023
Other							
Sup. Temporal G	L	42	−63	−26	14	12.48	0.005
Pallidum	R		18	−8	2	7.63	0.014
Cerebellum	L		−4	48	−6	6.08	0.02

Statistical significance according to FDR adjustment with $P < 0.05$; minimal cluster size: 10 voxels

Hem Hemisphere (*L* left, *R* right); *BA* Brodmann's area; *FDR* False Discovery Rate; *G* Gyrus; *S* Sulcus; *Sup* superior; *Inf* inferior; *IFS* inferior frontal sulcus; *SFS* superior frontal sulcus; *SMA* supplementary motor area; *ACC* anterior cingulate cortex; *IPS* intraparietal sulcus

ferences between the modality-compatible and modality-incompatible dual tasks, $t(9) = 0.966$, $P > 0.3$. Therefore, the results of the more sensitive ROI analysis based on the individual ROI masks are reported in greater detail, below.

Figure 3 shows the location of the ROI masks that were individually determined for each participant and that were used for the extraction of the β-values. The corresponding local maxima per participant are presented in Table 3. Nine out of ten participants revealed significant dual-task-specific activations along the left IFS. Participant 9 did not have any suprathreshold activations in the banks of the IFS. We used the data from the neighboring peak in the MFG instead. As can be seen in Fig. 3, the exact location of the individually determined local maxima varied largely across the whole IFS. For some participants, the local maximum was in the posterior part of the IFS close to the junction with the precentral sulcus, while other participants revealed activity peaks located in the middle part of the IFS. Also, the exact location varied from lateral parts of the IFS to more medial regions. There was virtually no overlap between participants in the location of their local maxima.

This finding goes beyond the results of the group analysis. The group analysis shows the most consistently activated region along the IFS across all participants, and the individual ROI analysis shows the location of the highest dual-task-specific activation along the IFS within each individual.

In order to address the main question of this study, namely, whether modality compatibility modulates dual-task-related activation in the IFS, we compared the β-values for the modality-compatible and modality-incompatible dual tasks within the individually determined dual-task-specific regions. Figure 4 depicts these β-values for the dual-task blocks. In addition, we present the β-values for the modality-compatible and modality-incompatible single tasks, which are summed for both corresponding single task blocks. As can be seen in Fig. 4, the amount of fMRI activation as measured by β-values is increased in modality-incompatible dual tasks compared to modality-compatible ones, $t(9) = 2.28$, $P < 0.05$. Thus, as predicted, the amount of activation in regions surrounding the IFS is modulated by the modality compatibility of the component tasks. This interpretation is confirmed by the results of the corresponding ANOVA with repeated measures (factors modality compatibility, task type) on the β-values in the different task conditions. It revealed a significant interaction of task type × modality compatibility, $F(1,9) = 5.87$, $MSE = 6.20$, $P < 0.05$, on the β-values. This interaction is due to the difference between the β-values in the modality-incompatible and modality-compatible dual tasks (see above), since the β-values did not differ
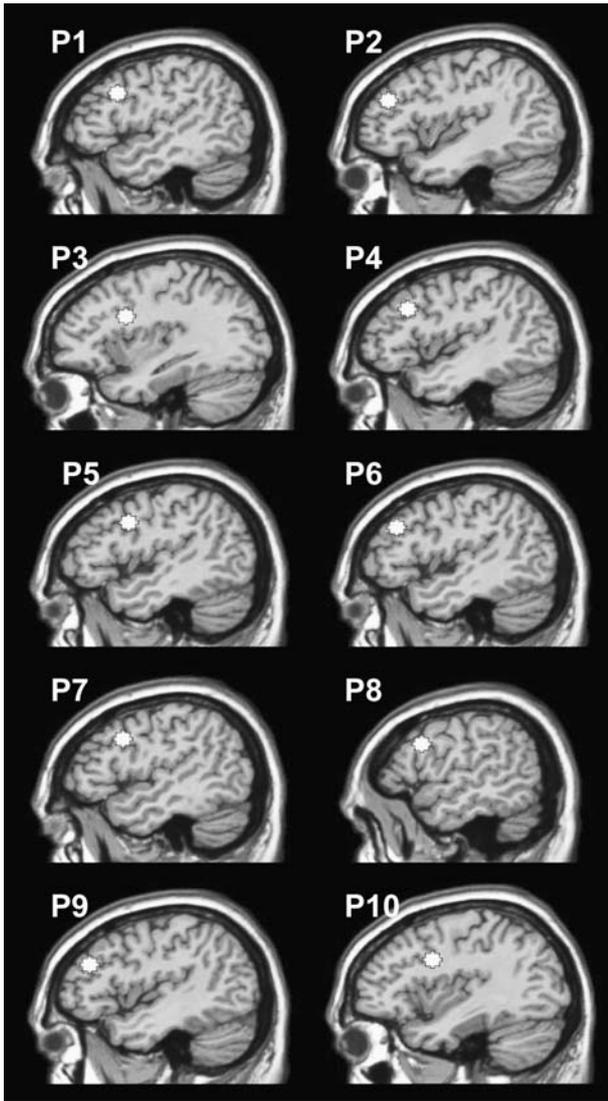
Fig. 3 Spherical ROI masks in the IFS for every participant. These masks were obtained from the contrast [(DUAL-COMP − FIX) + (DUAL-INCOMP − FIX)] − [(SINGLE-VM − FIX) + (SIN-GLE-AV − FIX) + (SINLGE-VV − FIX) + (SINGLE-AM − FIX)]. The local maxima of every participant (see Table 3) along the IFS were used as the center for the 4 mm masks. From these masked regions the mean β-values for all tasks were extracted. *P* Participant

between the corresponding single-task conditions, $t(9) = 0.42$, $P > 0.6$.

The ANOVA revealed further that, in general, dual tasks evoked higher activation in the IFS region than single tasks, $F(1,9) = 7.87$, $MSE = 53.56$, $P < 0.05$, thus, confirming the findings of the group analysis. The dual-task effect, as determined by the difference between β-values in dual task and β-values summed over both single-task conditions, was significant for the compatible, $t(9) = 2.49$, $P < 0.05$, and incompatible conditions $t(9) = 2.87$, $P < 0.05$, albeit higher for the modality-incompatible condition. Note that the interpretation of the latter effects must be made with caution because the considered dual-task versus single-task effects are not

truly orthogonal to the contrasts the ROIs were determined from.

Discussion

In the present study, dual tasks consisting of two modality-incompatible tasks (i.e., visual–vocal and auditory–manual) produce increased dual-task costs as compared to dual tasks consisting of two modality compatible tasks (i.e., visual–manual and auditory–vocal). This replicates findings from previous studies of Hazeltine et al. (under review) and Levy & Pashler (2001). More importantly, the fMRI data show that the increased dual-task costs are associated with increased activation of the IFS. The modality-incompatible dual task produced significantly higher signal changes along the IFS than the modality-compatible dual task.

The present results extend the findings of Szameitat et al. (2002, 2005) who showed that the amount of dual-task-related activity in the IFS depends on the demands on temporal order coordination. The dual tasks in the present study did not differ in their demands on the coordination of temporal order because both component tasks were presented simultaneously on each trial and participants were instructed to perform the tasks in a predetermined order. Since participants could implement one processing order throughout a dual-task block, temporal order coordination, as proposed by Szameitat et al. (2005), cannot explain the increased dual-task-related IFS activation in our study. Instead, the present data suggest that the coordination of concurrent mapping processes between stimulus and response modalities is directly associated with increases in the neural activity in cortical regions surrounding the IFS.

Taken together, these findings reveal a general role of the IFS in the coordination of interfering processes in dual-task situations. This is consistent with recent approaches on dual-task processing assuming the involvement of executive processes, actively scheduling potentially interfering processing stages (DeJong, 1995; Meyer & Kieras, 1997; Schubert & Szameitat, 2003). Whether coordination is a specific process and whether the nature of central capacity limitations in a dual-task situation is structural (Pashler, 1994; Schubert, 1999) or strategic (Meyer & Kieras, 1997; Schumacher et al. 2001) seems to be an open question at present. The presented neuroimaging data as well as those of Szameitat et al. (2002, 2005) suggest that, in general, these coordination processes are associated with increased neural activity in the IFS.

Mechanisms of modality compatibility

The finding of increased activation in the IFS related to modality compatibility raises the question of the precise

Table 3 Local maxima along the IFS in each participant

Partic.	Talairach coordinates			t value
	x	y	z	
1	−48	17	29	13.6
2	−42	38	22	8.2
3	−36	11	23	9.6
4	−44	25	28	9.2
5	−46	9	31	4.3
6	−46	32	26	10.1
7	−48	13	31	6.4
8	−53	15	27	17.5
9	−44	36	18	11.4
10	−38	7	27	10.9

Note. These peaks were determined by analyzing all runs in each participant. To ensure the reliability of peak locations, we split each data set in two equal sets and compared the coordinates of peak activations determined in the first set of runs with the coordinates reported here. Paired t-tests revealed no significant difference between the peak coordinates reported here and the peak coordinates determined in the first half of runs (all Ps > 0.4)

cognitive mechanisms underlying the effects of this factor. As shown in the behavioral data, the modality-incompatible dual task was clearly more difficult to process than the modality-compatible one. The reason for this higher difficulty presumably lies in some inherent characteristics of the stimulus and response pairings that make it easier to associate simultaneously a visual stimulus with a manual response and an auditory stimulus with a vocal response than the other way around. What could these characteristics be?
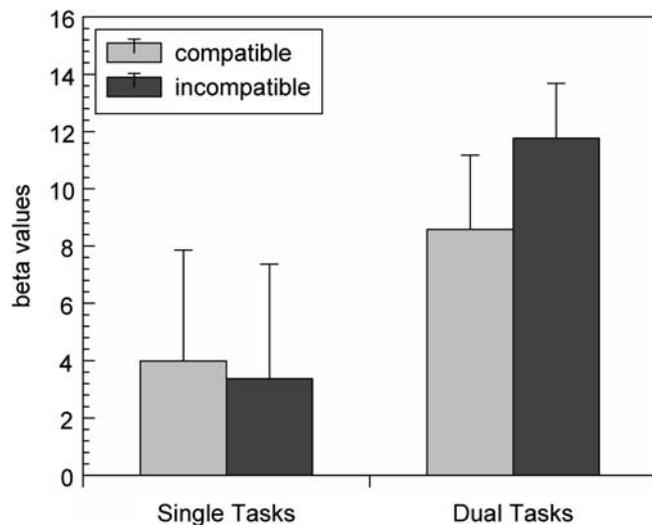
A potential theoretical explanation for this effect is given by the translational model proposed by Virzi &

Fig. 4 β-values averaged over all participants. The data were extracted from the individually defined ROIs depicted in Fig. 3. Data for the single tasks were summed for the two modality compatible and incompatible tasks, respectively. *Error bars* denote the standard errors

Egeth (1985). This model was proposed to account for modality-dependent interference effects in the Stroop task. According to this model there are modality-specific processing systems (e.g., spatial, linguistic) each of which codes and processes information in a way that is specific to that system. Input to one system must undergo translation if it is to be associated with a response modality of the other system. Most important to our findings is the assumption that the translation process works serially and interference arises when two different stimuli try to access the translation process simultaneously. According to this model, visual–vocal and auditory–manual tasks both need translation because the stimuli have to be associated with responses from another modality-specific processing system. Additional interference at the translation stage would then cause the higher cognitive requirements reflected in the increased dual-task costs and the higher activity in the IFS for the modality-incompatible dual task.

However, the model also assumes that translation itself takes time and, therefore, it would be reflected in corresponding behavioral costs in the single tasks as well. Critically, we did not find any differences between the RT and error data in modality-compatible and modality-incompatible single tasks. In addition, we also did not find any differences in the fMRI data of the single tasks depending on modality compatibility. Therefore, the assumption of an additional translation process causing increased dual-task costs and fMRI activation for modality-incompatible dual tasks as compared to modality-compatible ones cannot be correct.

A related explanation, focussing on the neural basis of interference, holds that increased dual-task costs in modality-incompatible situations stem from direct interference between processes in different modality-specific processing systems (Friedman & Polson, 1981; McLeod, 1977; Wickens, 1980). Evidence for the existence of such modality-specific processing systems can be found in the neuroscience literature. For example, Milner & Goodale (1995) delivered evidence for the existence of a visuo-motor system processing the spatial characteristics of motor actions in the visual domain. Other authors reported evidence suggesting the existence of specialized neural pathways for the processing of auditory information and planning speech responses (e.g., Liberman & Mattingley, 1989; Scott & Johnsrude, 2003), i.e. an auditory-speech system. This coupling of perceptual and motor processes is also suggested in Greenwald's (1970) ideomotor theory, which assumes that certain motor responses can be directly activated when the stimulus characteristics closely resemble the sensory feedback of the motor response on that stimulus.

For the present study, this means that the visual–manual and the auditory–vocal component tasks in the modality-compatible condition may involve two separate modality-specific neural systems, thus avoiding interference between the input and output modalities.

On the contrary, in a modality-incompatible dual task the processing of the auditory–manual component task involves structures of the auditory-speech system as well as of the visuo-motor system. However, parts of both systems are also needed for the processing of the other component task—the visual–vocal task. For example, it has been shown that the processing of tonal information employs brain structures classically associated with language processing (e.g., Koelsch, Gunter, von Cramon, Zysset, Lohmann, & Friederici, 2002). Critically, this common system might be needed for the processing of the auditory stimulus in the auditory–manual task as well as for the production of the vocal response in the visual–vocal component task. Thus, the neural substrates used for the S-R mapping processes of the two modality-incompatible tasks should partly overlap in a dual-task situation, thus, causing interference (e.g. Kinsbourne & Hicks, 1978). This would explain why we found increased processing demands in modality-incompatible situations only under dual-task conditions and not under single-task ones.

In addition to this modality-specific interference of mapping processes, increased dual-task costs in the modality-incompatible dual task might be caused by an overlap of abstract representations (i.e. codes) of the two tasks (see Koch & Prinz, 2002). An obvious code overlap between the two tasks concerns the left–right dimension present in the visual–vocal task as well as in the auditory–manual task. A post hoc analysis of cross-task compatibility effects, e.g. the influence of code overlap on reaction times in the modality-incompatible dual task, revealed a difference of 55 ms for code-compatible trials (e.g. say "left" for the circle and press left for the tone) to code-incompatible trials (e.g. say "left" and press right), $t(9) = 6.99$, $P < 0.001$, reaction times on code-compatible trials being slower. Interestingly, the emergence of response-compatibility costs across tasks has been shown in other studies (e.g. Schuch & Koch, 2004) which suggest that these costs reflect recoding processes that are needed to assign overlapping response-related codes in close succession to different tasks (see also Hommel, Müsseler, Aschersleben & Prinz, 2001). Thus, code overlap modulates reaction times in the modality-incompatible dual task, but in our view it is unlikely that the increased reaction times in comparison to the modality-compatible dual task ($+206$ ms) are entirely based on this code overlap. The extent to which the coordination of mapping processes and the recoding of overlapping response-related codes contribute to the increased activation of the IFS that we found in this study needs to be determined in further experiments.

Taken together, we presume that the increased activity in the IFS for the modality incompatible dual task reflects additional cognitive requirements that are needed to resolve the interference of mapping processes caused by an overlap of the neural systems involved in the processing of the component tasks.

Relationship to other studies on interference processing

The presumed general role of the IFS in dual-task coordination is questioned by a recent study of Jiang, Saxe & Kanwisher (2004). These authors used, similar to our study, a parametric design to investigate the changes in neural activity, which are associated with different demands on interference processing. For that purpose, they manipulated the temporal overlap of both tasks by varying the stimulus onset asynchrony (SOA). Differently to the findings of the present study and those of Szameitat et al. the parametric manipulation did not lead to activity changes in lateral prefrontal regions. The authors concluded that the lack of activity in regions associated with executive functions supports the view that interference processing at short SOAs does not involve more active coordination processes than task processing at long SOAs and therefore is not associated with additional activation of the IFS. With respect to the findings of the present study, such a conclusion has to be interpreted with caution because of the reported null result. In addition, Jiang and colleagues analyzed the dual-task-related activation exclusively on a group level. A detailed analysis of individual activation maps as performed in the present study might have given further insights into the reasons for this null result. Perhaps, high variability in the anatomical and functional organization of higher cognitive functions between participants made the analysis of such fine-grained cognitive mechanisms on a group level very noisy. Individual methods of data analysis allow taking this variability into account and provide a powerful extension to the report of group activation clusters (see also Miller et al. 2002).

The role of the IFS in the coordination of interfering task processes has also been shown in a number of studies using paradigms outside the dual-task domain. For example, increased activation of the IFS was found in task-switching paradigms (Dove et al. 2000), in the Stroop paradigm (Milham et al. 2001; Zysset et al. 2001), in Eriksen–Flanker tasks (Bunge et al. 2002), or incompatibly mapped response-selection tasks (Iacoboni et al. 1996; Jiang & Kanwisher, 2003; Schumacher et al. 2003). Based on these findings, as well as on our findings, we conclude that the management of interference between competing processes seems to be a generalized function of the cortical regions surrounding the IFS.

In sum, in the present study, we showed that the compatibility of stimulus and response modalities modulates neural activity along the left IFS. Our findings are consistent with the assumption that the IFS is involved in the coordination of concurrent mapping processes between stimulus and response modalities in a dual-task situation. This supports the view that the IFS plays a general role in the coordination of interfering task processes in dual-task situations, which is not restricted to the coordination of temporal order.

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