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Concurrent multitasking

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CHAPTER 2

Single-task fMRI Overlap Predicts Concurrent Multitasking Interference

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Where we look in the brain for evidence of cognitive interference between tasks.

Single-task fMRI Overlap Predicts Concurrent Multitasking Interference

Abstract

There is no consensus regarding the origin of behavioral interference that occurs during concurrent multitasking. Some evidence points toward a multitasking locus in the brain, while other results imply that interference is the consequence of task interactions in several brain regions. To investigate this issue, we conducted a functional MRI (fMRI) study consisting of three component tasks, which were performed both separately and in combination. The results indicated that no specific multitasking area exists. Instead, different patterns of activation across conditions could be explained by assuming that the interference is a result of task interactions. Additionally, similarity in single-task activation patterns correlated with a decrease in accuracy during dual-task conditions. Taken together, these results support the view that multitasking interference is not due to a bottleneck in a single "multitasking" brain region, but is a result of interactions between concurrently running processes.

Introduction

There is often a cost to simultaneous performance of multiple tasks as compared to doing only one task at a time. Discovering the source of this interference has been one of the main goals of multitasking research, and explanations of this phenomenon have been formalized within several theoretical frameworks (e.g., Just & Varma, 2007; Meyer & Kieras, 1997; Salvucci & Taatgen, 2008, 2011; Wickens, 2002). Although a relatively coherent image has emerged of the behavioral effects of multitasking, the underlying brain mechanisms are less well described. An important remaining question is whether multitasking interference is caused by interference in a single, universal, "multitasking" brain region (henceforth referred to as the multitasking locus) or that it is the result of widespread interactions in the brain.

The origin of the multitasking locus concept can be attributed to several theories of executive control (Baddeley, 1986; Shallice, 1988; Miller & Cohen, 2001; Conway et al., 2003). According to these theories, a so-called 'central executive' manages the selection of cognitive functions and actions, and thus facilitates the coordination of concurrent cognitive processes, as required during multitasking. To date, several neuroimaging studies have identified "multitasking" brain regions that correlated with dual-task interference, and therefore could include a multitasking locus (e.g., Collette et al., 2005; Dux et al., 2006; Herath et al., 2001; Szameitat et al., 2002; Wu et al., 2013). However, other studies have concluded that no such areas exist (e.g., Adcock et al., 2000; Erickson et al., 2005; Jaeggi et al., 2003; Just et al., 2008; Just et al., 2001; Klingberg, 1998). The main variable in these diverging results seems to be the experimental paradigm, indicating that the neural correlates of multitasking interference are strongly influenced by the properties of the particular tasks that were used. This is in agreement with most recent behavioral theories, which assume that multitasking interference is a result of overlapping resource use between specific tasks, and therefore task dependent (Meyer & Kieras, 1997; Salvucci & Taatgen, 2008, 2011; Wickens, 2002).

Following these results and recent theories on multitasking, we hypothesize that the particular expression of multitasking interference in the brain depends on the specific tasks that are combined. The underlying idea is that different tasks require different cognitive and peripheral resources, which leads to different patterns of resource overlap. We have previously shown that behavioral interference between tasks indeed depends on their overlap in resource requirements – the higher the overlap in resource use, the more multitasking interference (e.g., Borst, Taatgen, & Van Rijn, 2010; Borst et al., 2013; Nijboer et al., 2013; Salvucci & Taatgen, 2008, 2011). However, this concept of task-dependent interference patterns has not been tested directly for neural activation. Previous dual-task neuroimaging studies that focus on task overlap have typically only investigated a single pair of component tasks (Herath et al., 2001; Just et al., 2001; Klingberg, 1998; Roland & Zilles, 1998), or different input and output modalities within the same task combination (Mochizuki

et al., 2007). Yet multiple combinations of tasks that are conceptually different (and therefore separable in terms of resource use and strategy) must be compared to assess if the observed dual-task activation is specific to that particular combination of tasks, or generalizes to more than one dual-task setting. In addition, this idea implies that one could determine the (in)compatibility of tasks by comparing their single-task brain activation. If single-task brain activation is an index of resource use of a task, the higher the overlap in the elicited single-task brain activation between pairs of tasks, the higher their multitasking interference should be.

To test if neural multitasking-interference patterns are task-dependent, and whether single-task brain activation predicts multitasking interference, we performed a functional magnetic resonance imaging (fMRI) experiment with three different tasks. Subjects performed the three tasks separately, as well as all possible combinations of these tasks. This allowed us to investigate the relation between single task resource use and neural activation, and the effect thereof on multitasking interference patterns. In addition, we tested the strong prediction that single-task activation patterns can be used to predict multitasking interference between tasks. In the remainder of this introduction, we will give an overview of the multitasking fMRI literature and a detailed description of the current study.

Neuroimaging Studies of Multitasking Interference

Dual-task neuroimaging studies have shown diverse results. The differences in the percent signal change of the BOLD response can be divided into three categories: over-additive, additive, and under-additive activation in regions involved in the dual-task condition. Studies that found over-additive activation have typically found recruitment of regions exclusive to the dual-task condition. These studies have implicated areas of the prefrontal cortex (Collette et al., 2005; Dux et al., 2006; Herath et al., 2001; Szameitat et al., 2002), as well as parietal regions (Collette et al., 2005; Herath et al., 2001) as playing an important role in managing the concurrent execution of tasks. Furthermore, studies have also found over-additive activation in areas that were already active during performance of the component single-tasks (e.g., the prefrontal cortex and cerebellum; see Schubert & Szameitat, 2003; Wu et al., 2013). Several hypotheses have been proposed for these dual-task specific areas. First, such an area could be a serial bottleneck stage in the management of two concurrently performed tasks (Herath et al., 2001; Szameitat et al., 2002). Second, the indicated regions could be a part of the executive control system that manages dual-tasking (Collette et al., 2006).

Other studies have found additive activation, where the percent signal change in the dual-task was the summation of activation in the component tasks (Adcock et al., 2000; Erickson et al., 2005; Jaeggi et al., 2003). Contrary to studies that find over-additive results, additive activation has been argued to indicate that there are no brain regions involved specifically in dual-task processing. Adcock et al., (2000) implied that interference is the result of an overlap between systems required for each component

task: as both component tasks utilize the same resources (e.g., visual or memory systems), the resource requirements of the dual-task are the combined requirements of the component tasks. Consequently, the observed dual-task activation is simply the summation of the component task activation.

Finally, there is evidence that a dual-task can produce under-additive activation. In this context, under-additive indicates that the increase in activity during the dual-task is less than sum of the activity in the component single-tasks (Buchweitz et al., 2012; Klingberg, 1998; Newman et al., 2007). These under-additive effects can be strong: Just et al., (2001) reported that activity in temporal and parietal areas during a dual-task was less than the activity measured during either of the component tasks. Several theories have been proposed to explain under-additive activation: according to Just & Varma (2007), there is a limit on the amount of active cortical tissue, which might require the activity to be divided amongst more areas during a dual-task[1]. In contrast, Anderson et al. (2011) argued that during multitasking there is competition for cognitive resources between tasks, resulting in one task taking away time-on-resource from another task, which leads to activity that is lower than the sum of the component tasks.

One factor that seems to play a role in these divergent results is task modality, as tasks performed in different modalities have led to different results (Hazeltine et al., 2006; Mizuno et al., 2012; Mochizuki et al., 2007). For example, Newman et al. (2007) suggested that significant prefrontal activity would only occur if the same input modality were used for all stimuli categories. More generally, the type of task used in the dual-task condition seems to determine the patterns of neural activity that are found. A large number of studies use the discrete task-choice (or PRP) paradigm (e.g., Collette et al., 2005; Hazeltine et al., 2006; Herath et al., 2001; Schubert & Szameitat, 2003; Szameitat et al., 2011), whereas others use more dynamic tasks and stimulus interleaving schedules (e.g., Just et al., 2001; Just, et al., 2008; Mizuno et al., 2012; Newman et al., 2007; Wu et al., 2013). Comparing these studies suggest that more dynamic and complicated dual-task settings have a tendency to show under-additive activation, while PRP paradigms typically show additive and over-additive activation; a point previously raised by Just et al. (2007). Their explanation was that if concurrently performed tasks were simple enough, they would not exceed the upper limit of total activation, allowing for an additive or over-additive Blood-Oxygenation Level-Dependent (BOLD) increase.

Paradigm

To investigate if and how patterns of performance and neural activity change depending on what tasks are combined we used three different tasks – n-back, tracking, and tone-counting – and a total of six conditions: three single-tasks plus all three possible dual-task combinations. The tasks were chosen such that the dual-task

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[1] Such a limit could also be used to explain additive activation: complex processes that potentially lead to over-additive activation reach the activation limit, therefore only displaying additive activation.
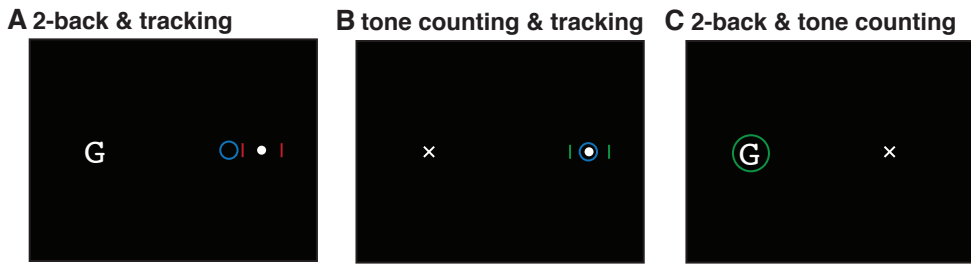
A 2-back & tracking   **B tone counting & tracking**   **C 2-back & tone counting**

Figure 2-1. The three dual-task screens as presented to the participants. *Panel A:* The left side of the screen shows a stimulus of the 2-back task, with the right side showing the tracking task. In the tracking task, the vertical lines indicate the maximum allowed distance between the cursor (blue circle) and the target (white dot). They are colored red when the cursor is outside this boundary. *Panel B:* Left tone-counting, right tracking, with a correct cursor position. *Panel C:* Left 2-back, with the green circle indicating a correct response, and right the tone-counting task.

combinations resulted in different resource conflicts.

N-back: In the n-back task a stream of letters was presented on screen. For each letter shown after the nth letter, the participant had to respond whether the letter was the same or different as the letter seen n presentations ago (Figure 2-1A & 2-1C). In this experiment, we used a 2-back task. The n-back task was predicted to use motor, visual, and working memory (WM) resources (Juvina & Taatgen, 2007; Owen et al., 2005).

Tracking: The goal of the tracking task was to keep a cursor centered on a dot that randomly moved from left to right (Martin-Emerson & Wickens, 1992). Some degree of error was tolerated, conveyed by two lines flanking the dot (Figure 2-1A & 2-1B). The tracking task was predicted to use motor and visual resources (Chavez & Salvucci, 2003).

Tone-counting: Low and high pitch tones were presented in a random order at different intervals. Subjects were instructed to count the high pitch tones and ignore the low pitch tones. The total number of high pitch tones had to be entered at the end of the trial. The tone-counting task was expected to use aural and WM resources during the trial, and the motor resource when entering the response.

In the current paradigm, the three dual-task combinations show different patterns in overlapping resource use. When tone-counting is paired with tracking, no overlap is predicted: the tasks have different stimulus modalities, as well as different times when motor input is required. When 2-back is paired with tracking, there is peripheral overlap: both tasks use visual and motor resources. Finally, when 2-back is paired with tone-counting the overlap is primarily cognitive, as both tasks use WM, but no peripheral overlap is predicted. Our assumed definition of WM within this study is similar to the focus of attention (Borst, Taatgen & Van Rijn, 2010; McElree, 2001; Oberauer, 2002): it can contain only a single chunk of information. Access to

several chunks requires swapping a chunk between this focal WM and declarative memory (DM), where the other chunks that need to be remembered are maintained. Although there are two dual-tasks with a fair degree of overlap, we still expected to see differences in performance and neural activity between both conditions due to the type of resources overlapping: earlier research into multitasking interference has indicated that cognitive overlap can lead to a more severe performance reduction than peripheral overlap (Borst et al., 2013; Nijboer et al., 2013; Salvucci & Taatgen, 2010).

To provide evidence for a multitasking locus, all three dual-tasks would need to show over-additive activation in the same region. If, however, the resulting dual-task activations strongly resemble the summation of the activity found in the single-tasks, then it is more likely that multitasking interference is a result of cortical overlap between processes.

Methods

Participants

A total of 20 right-handed adults participated in the study. The study was approved by the Medical Ethical Committee of the University Medical Centre Groningen, and written informed consent was obtained before the study. Participants received €25 for their participation. All participants had normal or corrected-to-normal vision. One participant did not adhere to the task instructions and was removed from the dataset, leaving 19 participants for analysis (14 female, M_{age} = 22.4, age range: 18-27).

Materials and Procedure

The experiment consisted of the three previously introduced tasks: n-back, tracking, and tone counting. These tasks were presented as single tasks and as dual-tasks (all three combinations: n-back plus tracking, n-back plus tone counting, and tracking plus tone counting). The participants had a four-button response box resting on their abdomen during the fMRI session, with their left index and middle fingers positioned on the two left-most buttons, and their right index and middle fingers positioned on the two right-most buttons. Table 2-1 gives a full overview of task-response mappings. The experiment was projected onto a mirror mounted to the fMRI head-coil, with stimuli (see below) on a black background.

For the 2-back task, each letter was shown for 1000 ms, followed by blank screen of 1500 ms. In total, 12 letters were presented per trial. Participants were instructed to use the button positioned under their left middle finger to indicate that the letter was the same as two letters back, and the button under their left index finger if the current letter was different from two letters back. Participants had 1500 ms to respond, starting at the presentation of each letter. Feedback was provided in the form of a green or red circle around the letter for a correct or incorrect answer, respectively.

Hand	Finger	Action
2-back		
Left	Index	Different
Left	Middle	Same
Tracking		
Right	Index	Move cursor to the left
Right	Middle	Move cursor to the right
Tone counting (combined with 2-back)		
Right	Index	Increment the tens of the answer
Right	Middle	Increment the ones of the answer
Tone counting (combined with tracking)		
Left	Index	Increment the ones of the answer
Left	Middle	Increment the tens of the answer

Table 2-1. Response mappings between fingers and tasks.

Feedback remained visible during the ISI.

The tracking cursor controlled by the participant was shaped as a blue circle, while the target was a white dot. The target only moved in a horizontal direction across the screen. Participants could move the cursor to the left using the button under their right index finger, and to the right using the button under their right middle finger. Flanking the dot were two vertical lines that indicated the maximum tolerated distance between the cursor and target. The color of the lines changed from green to red if the cursor was outside those two lines. On average, the tracking task required 2.4 responses per second.

The tone-counting task consisted of 20 tones presented at pseudo-random intervals (ranging between 0.5 and 1.5 seconds). High tones had a pitch of 493.99 Hz (a B_4 note) and low tones of 261.63 Hz (a C_4 note) to make them easily distinguishable. The number of high tones was randomized per trial; sampled from a uniform distribution ranging from 10 to 17. As the tone-counting tasks contained no visual stimuli, a fixation cross was shown instead. The answer prompt was presented for 9.5 seconds after the trial. During this prompt, participants could indicate their response by incrementing the displayed number using the response buttons (either the buttons under their left hand index and middle finger when tone counting was performed together with 2-back, and the buttons under their right hand otherwise). The displayed numbers loop; pressing the button when the digit read 9 would cause 0 to reappear. After the response period, feedback indicating correct or incorrect was presented for 500 ms.

Before each trial a fixation cross was presented for eight seconds. Afterwards, the names of the tasks involved in the upcoming trial were displayed for two seconds, after which the trial would start. The 2-back task was always presented on the

left side of the screen, and the tracking task always on the right side. The fixation mark associated with tone-counting was displayed on the other side. Trials lasted 30 seconds, except trials that included tone-counting, which had an additional 9.5 seconds at the end for the response phase.

Participants first performed a practice session of two blocks outside of the scanner. Each block contained two trials of each condition and a fixation-only trial. In fixation-only trials participants only had to look at the center of the screen. This amounted to 13 trials per block, which took approximately ten minutes. Condition order within a block was randomized. In the scanning session, participants started with a single practice block, followed by six experimental blocks. Thus, participants completed 78 experimental trials: 12 per condition and six fixation-only trials.

fMRI Procedures and Preprocessing

The neuroimaging data were obtained with a Philips Interna 3 Tesla scanner using a standard radio-frequency head coil. Each functional volume consisted of 37 axial slices (3.5 mm thickness, 64x64 matrix, 3.5 mm x 3.5 mm per voxel), acquired using echo-planar imaging (2000 ms TR, 20 ms TE, 70° flip angle, 224 mm field of view, 0 mm slice gap, with AC-PC on the 19th slice from the bottom). Anatomical images were acquired using a T1-weighted spin-echo pulse sequence with the same parameters as the functional images, but with a higher resolution (1 mm thickness, 256x256 matrix, 1 mm x 1 mm per voxel).

The data were preprocessed using SPM8[2]. The steps consisted of realigning the functional images, co-registering them with the structural images, normalizing the images to the MNI (Montreal Neurological Institute) ICBM 152 template, and smoothing them with an 8 mm FWHM Gaussian kernel.

Results

Behavioral Results

Unless mentioned otherwise, all *F*- and *p*-values are from one-way repeated-measure ANOVAs, and all accuracy data were transformed with a logit transformation before performing ANOVAs. Comparisons were done using a Tukey honest significant difference. All error bars depict 95% confidence intervals (CI). Statistical results are reported in Tables 2-2 and 2-3.

Figure 2-2A shows that for the 2-back task participants were less accurate in both dual task conditions compared to the single-task. There was a main effect of condition, and planned post-hoc comparisons indicated that all three conditions differed significantly ($p < .001$). Of the two dual-task conditions, accuracy decreased most in the 2-back plus tone-counting condition (a 14% vs. 6% difference). The 2-back latency data in Figure 2-2C did not mirror the pattern seen in the accuracy

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[2] Wellcome Trust Centre for Neuroimaging (http://www.fil.ion.ucl.ac.uk/spm/)

Measure	$F(2,36)$	n_p^2	p
2-back accuracy	57.01	0.76	<.001
2-back response time	47.84	0.73	<.001
Tone-counting error	28.74	0.61	<.001
Tracking accuracy	40.86	0.69	<.001

Table 2-2. Analysis of reaction time and accuracy data. One-way ANOVAs were computed for each measured performance variable (across all three conditions where this measure would occur) to test for an overall effect.

Comparisons	2-back accuracy			2-back response times		
	z	β	p	t	β	p
2b vs. (2b + Co)	-10.66	-1.67	<.001	4.14	0.06	<.001
2b vs. (2b + Tr)	-5.91	-0.92	<.001	9.74	0.13	<.001
(2b + Co) vs. (2b + Tr)	4.75	0.74	<.001	5.61	0.08	<.001

Comparisons	Tone-counting error			Tracking accuracy		
	z	β	p	z	β	p
Co vs. (Co + Tr)	< 1	-	-			
Tr vs. (Co + Tr)				2.75	0.31	.017
Co vs. (2b + Co)	6.86	0.81	<.001			
Tr vs. (2b + Tr)				8.83	0.99	<.001
(2b + Co) vs. (Co + Tr)	6.23	0.73	<.001			
(2b + Tr) vs. (Co + Tr)				-6.08	-0.68	<.001

Table 2-3. Comparisons between conditions for reaction times and accuracy data. Abbreviations: 2b = 2-back, Co = tone-counting, and Tr = tracking. Comparisons were computed by applying a Tukey honest significant difference on a linear mixed-effects model, which contained the same factors as the one-way ANOVAs of Table 2. Significance was not reported for z values smaller than one.

data. Again, there is a main effect of condition, and post-hoc tests indicated that all three conditions differed significantly ($p < .001$). The single task resulted in the fastest responses, while 2-back plus tracking condition had the slowest 2-back reaction times.

Tracking error, defined as the percentage of the trial where the cursor was not between the vertical lines, was low in all conditions (Figure 2-2B). Compared to the single task, the error was slightly higher in the dual tasks: there was a main effect of condition, with the 2-back plus tracking condition differing the most from the single-task (2-back plus tracking: 7% difference; $p < .001$; tracking plus counting: 1% difference; $p = .017$).

Finally, error distance for the tone-counting condition is shown in Figure 2-2D. There is a main effect of condition, and the 2-back plus tone-counting condition showed a large increase in error distance compared to the single-task ($p < .001$). The
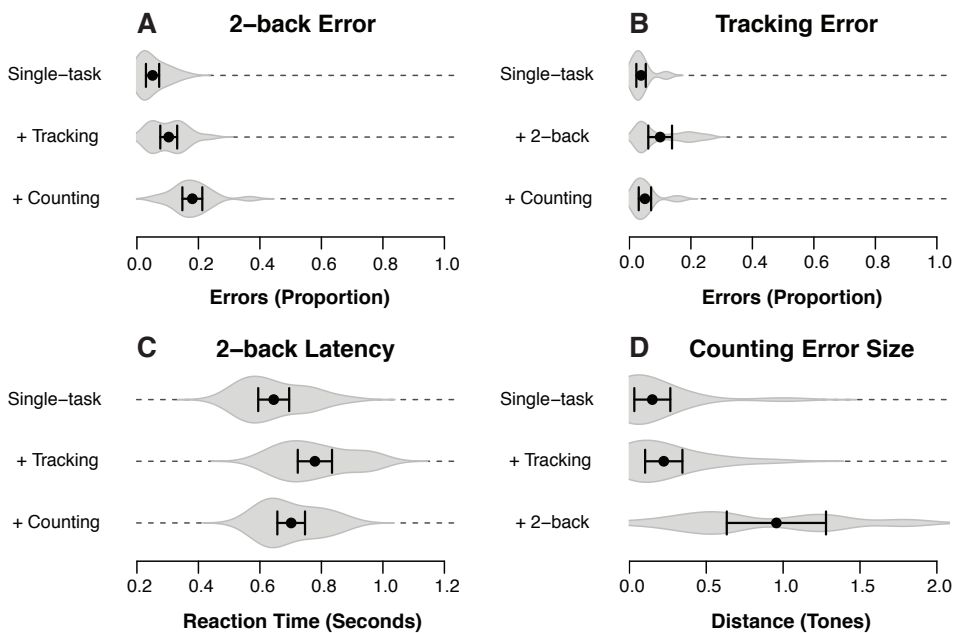
Figure 2-2. Behavioral data. Black dots represent the mean across subjects, and bars denote 95% CI. Gray volumes behind the means are (the smoothed estimates of) the underlying distribution of the data (Sheather & Jones, 1991). *Panel A:* The errors in the 2-back task, as the proportion of incorrect responses during a trial. *Panel B:* The tracking error, taken as the proportion of time off target. *Panel C:* Latency for the 2-back, taken as the response time for each letter. *Panel D:* Error size of responses to the tone-counting task. Values represent the distance to the correct answer in number of tones.

error distance of the single-task and tone-counting plus tracking condition did not differ significantly.

These results confirmed the idea that different combinations of tasks lead to different patterns of behavioral interference. The current set of tasks is therefore suitable to test our hypothesis of task-dependent brain activity interference patterns. If multitasking interference is better explained by a multitasking locus, brain region(s) need to show over-additive activity during the dual tasks, and the strength of this activation should correlate with the strength of the behavioral interference observed in each dual-task. If interference is better accounted for as an interaction between specific tasks, the similarity between activation elicited by component tasks should correlate with the change in accuracy during the dual-task.

Neuroimaging Results

Statistical parametric maps of all six conditions, relative to baseline, were generated. Significance was determined using a voxel-wise FDR (false discovery rate) correction at $p < .01$ and a minimum of 25 significant voxels per cluster. The maxima of significant

clusters are reported in Table 2-4 (single tasks) and Table 2-5 (dual tasks). In addition to whole brain analyses, we also performed region-of-interest (ROI) analyses. For these analyses we used the Bayesian t-test implemented in the BayesFactor package (Morey & Rounder, 2012). This approach was applied because finding evidence for additive activation (in contrast to over- or under-additive activation) requires evidence for the null hypothesis, which conventional frequentist statistics cannot provide.

Single-Task Activation

Maps showing activation compared to baseline for each condition are presented in Figure 2-3. When performed as a single-task, the 2-back task (Figure 2-3A) elicited widespread activity in both posterior and anterior regions of the brain: both inferior parietal lobules, the left dorsolateral prefrontal cortex, left ventrolateral prefrontal cortex, supplementary motor cortex (SMA), right premotor cortex, and right precentral gyrus were found to correlate significantly with the 2-back task. All of these regions have previously been linked to the n-back task in a meta-analysis by Owen et al. (2005). The tracking task (Figure 2-3B) elicited a large distribution of activity in the left precentral and postcentral gyrus, as well as bilateral recruitment of the superior parietal lobules. Other active clusters were found in the SMA, right cerebellum, thalamus, and hippocampus, as well as in the inferior and middle temporal gyri. The tone-counting task (Figure 2-3C) elicited bilateral activation in the superior temporal gyrus, the SMA, and the premotor cortex.

At first glance, the three dual-task conditions (Figure 2-3D to 2-3F) showed activity similar to the sum of their component tasks. To assess the similarities and differences between single-tasks and dual-tasks more precisely, we compared the underlying change in BOLD signal between conditions in the next section.

Single vs. Dual task

To determine the dual-task specific activation, we calculated contrasts as suggested by Szameitat et al. (2011). Specifically, we subtracted the activity of the relevant single-tasks from the dual-task for each participant. A group-level analysis of these contrasts resulted in three t-maps that show the surplus activity found in the dual-tasks relative to the single-tasks (Figure 2-4 A, B and C; refer to Table 2-6 for an overview of cluster maxima).

Tracking plus tone counting is shown in Figure 2-4A, and contains a single cluster of additional activation located along the calcarine sulcus. This area, also referred to as the primary visual cortex, indicates that the dual-task puts additional strain on the visual system. 2-back and tone-counting displayed activity in several regions. Again, dual-task specific activity was found in visual areas, indicating an increase in visual processing. Hippocampal activation can be distinguished as well, which could be indicative of a higher WM load (van Vugt et al., 2010). Finally, the 2-back plus tracking dual task shows a widespread cluster of activity that can be linked to

Brain region (BA)	2-back					Tone counting				
	Coordinates			t(18)	Size	Coordinates			t(18)	Size
	x	y	z			x	y	z		
L Dorsolateral PFC (9/46)	-42	2	28	5.45	217					
L Inf. parietal lobule (40)	-30	-52	46	7.61	350					
L Premotor cortex (6)						-48	-7	52	9.90	179
L Premotor cortex (6)						-54	2	19	5.29	47
R Premotor cortex (6)						54	-1	43	6.24	55
R Sup. temporal gyrus (22)						66	-28	10	11.63	474
L Sup. temporal gyrus (22)						-60	-31	10	8.60	490
Supplementary motor (6)	0	2	58	7.72	956	-3	-4	61	8.41	158
L Ventrolateral PFC (45/47)	-33	20	-2	6.35	49					
	Tracking									
R Cerebellum	18	-58	-23	9.27	307					
L Inf. temporal gyrus (37)	-48	-73	-2	9.21	144					
R Mid. temporal gyrus (37)	48	-58	-2	9.10	379					
R Precentral gyrus (4)	39	-10	52	6.73	47					
L Postcentral gyrus (3)	-54	-22	43	14.66	2015					
R Postcentral gyrus (1/2)	66	-28	25	6.22	121					
R Sup. parietal lobule (7)	18	-55	61	6.76	117					
L Thalamus	-15	-19	7	6.10	38					

Table 2-4. Single-task cluster maxima. Coordinates are in MNI space. All results have been corrected with a $p = 0.01$ FDR, and a minimal cluster size of 25. All reported t-values have $p < .001$.would occur) to test for an overall effect.

increased visual and motor processing: cerebellum, primary visual cortex, thalamus, and corpus callosum all present an increase in activation. Increased hippocampal activity is evident as well, much like that found in the 2-back and tone-counting condition. Furthermore, there is some additional activation in the rostral lateral prefrontal cortex.

To determine if any dual-task specific activation could be attributed to a multitasking locus, an intersection of all three t-maps was computed (Figure 2-4D). For example: activation unique to 2-back and tracking is indicated by red voxels, while green voxels were active in two dual tasks: 2-back and tracking, as well as 2-back and tone-counting. A multitasking locus should show activity in all three maps, and therefore appear as a white area in the overlay map. One white cluster does appear, located in the primary visual cortex. As all three maps dual-task specific maps show increased activity in areas related to visual processing, this is not unexpected. However, areas that are considered important in the management of concurrent processing streams are typically found in frontal, parietal, or cerebellar regions. Therefore it is likely this commonly activated cluster simply indicates that the dual-tasks in our paradigm result in increased visual processing.

Brain region (BA)	2-back and tone counting					2-back and tracking				
	Coordinates			t(18)	Size	Coordinates			t(18)	Size
	x	y	z			x	y	z		
L Calcarine sulcus (17)	-9	-82	1	11.88	3113					
R Calcarine sulcus (17)						6	-79	4	15.86	11825
R Hippocampus	33	-34	-2	5.72	362					
Corpus callosum	0	-37	22	4.58	44					
L Precuneus (7)	-12	-49	46	5.88	111					
R Mid. temp. gyrus (21)						48	-1	-14	5.17	85
R Putamen						30	14	-5	4.54	36
L Rostral lateral PFC (10)						-36	50	22	4.91	58
R Rostral lateral PFC (10)						33	56	16	3.99	30
L Frontal operculum (44)						-30	2	22	6.02	83
R Frontal operculum (44)						33	11	25	5.36	59
R Cingulate gyrus (24)						12	8	31	5.27	141
R Postcentral gyrus (2)						45	-25	49	3.87	44
	Tone counting and tracking									
R Calcarine sulcus (17)	15	-82	7	7.38	47					

Table 2-5. Coordinates are in MNI space. All results have been corrected with a $p = 0.01$ FDR, and a minimal cluster size of 25. All reported t-values have $p < .001$.

However, we cannot exclude the possibility that there was dual-task specific activity in regions found in previous studies. It could be that our analysis was not sensitive enough: the activity of other, commonly activated regions might be just below our chosen threshold. If so, our evidence of only finding increased visual activity would be weak. To address this possibility[3], we recalculated the dual-task specific activation maps (see Figure 2-4A, B and C for the $p < 0.01$ results) with a more liberal (but still acceptable) FDR of $p < 0.05$, and computed the intersection that can be seen in Figure 2-4E. This new intersection shows an additional large cluster, located in the corpus callosum. As the corpus callosum plays a role in the visual system (Berlucchi, 1972), this activity again seems indicative of increased visual processing. The corpus callosum has not previously been linked to the executive control of multitasking. Hence, much like the primary visual cortex, the corpus callosum does not seem to be a plausible multitasking locus.

ROI Analyses

To further investigate our data in relationship to previous neuroimaging studies of multitasking, we selected ROIs that fulfilled two criteria: First, prospective ROIs were areas that have previously been shown to correlate with dual tasking. Second, these prospective regions were active in one of the dual tasks found in the current study. The

[3] The problem is inherent to this type of analysis, and therefore cannot be fully resolved. See (Nieuwenhuis et al., 2011) for a more extensive discussion.
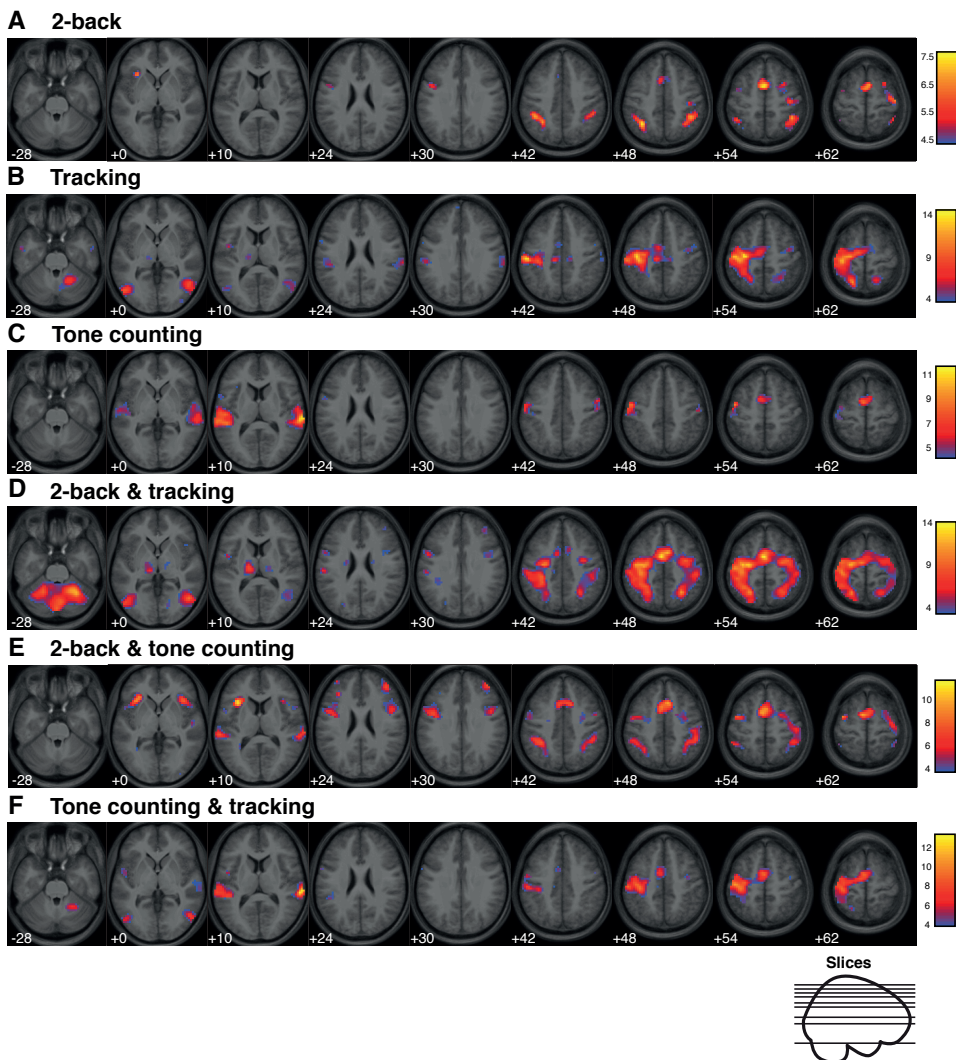
Figure 2-3. Supra-threshold voxels for all six experimental conditions, compared to baseline. Voxels are colored according to their corresponding *t*-value, as shown in the bars on the right. The brain outline in the top-right indicates the locations of the slices presented in the image sequences.

first criterion was chosen to investigate potential multitasking loci and the different types of activation summation (under-additive, additive, and over-additive) found in previous studies. The second criterion was chosen to limit the investigated areas to those that were found to show activity in the dual-tasks of the current paradigm: as brain morphology is unique to each individual, peak coordinates found in previous studies might not optimally reflect that region in the participants of the present study. These selection criteria were used to define nine ROIs.
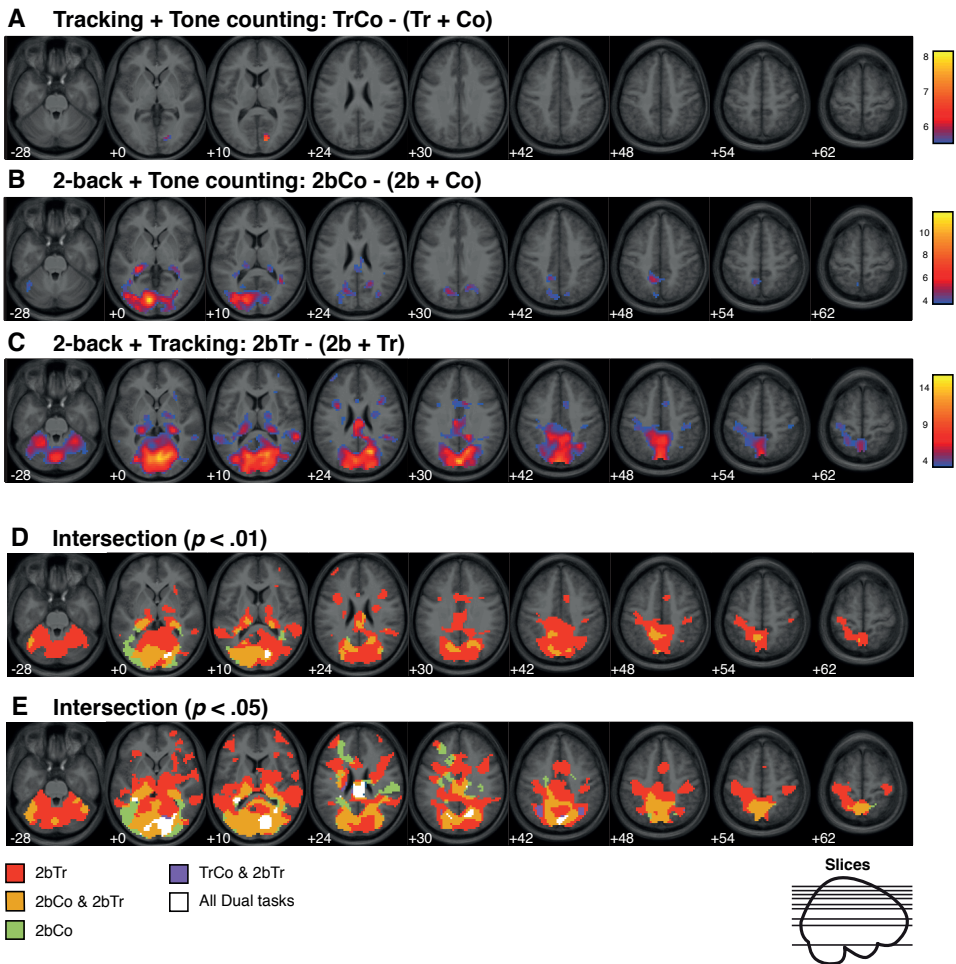
Figure 2-4. Dual-task specific activation. Maps A, B and C result from subtraction of the relevant single-tasks from the dual-task. Maps D and E visualize the intersection between the dual-task specific maps. Abbreviations: 2b = 2-back, Tr = tracking, Co = tone-counting. Overlap between active single-task and dual-task voxels is color coded according to the legend shown in the lower-right corner (e.g., a voxel is colored red if it was active during the 2-back plus tracking condition, but not during either other dual task).

For each target region, the ROI voxels were defined as a sphere with a radius of six mm. To determine the center point of the sphere, the appropriate supra-threshold clusters were identified in the dual-task t-maps[4]. The center of the sphere was defined by the local maxima in the targeted region (see Table 2-5). The exact location of

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[4] Circular reasoning (Kriegeskorte et al., 2009) does not apply here, as the ROI selection is based on a contrast between dual-task and the baseline, while the main ROI analysis is based on a contrast between a dual-task and its component tasks.

Brain region (BA)	2-back and tone counting					2-back and tracking				
	Coordinates			t(18)	Size	Coordinates			t(18)	Size
	x	y	z			x	y	z		
L Calcarine sulcus (17)	-9	-82	1	11.88	3113					
R Calcarine sulcus (17)						6	-79	4	15.86	11825
R Hippocampus	33	-34	-2	5.72	362					
Corpus callosum	0	-37	22	4.58	44					
L Precuneus (7)	-12	-49	46	5.88	111					
R Mid. temp. gyrus (21)						48	-1	-14	5.17	85
R Putamen						30	14	-5	4.54	36
L Rostral lateral PFC (10)						-36	50	22	4.91	58
R Rostral lateral PFC (10)						33	56	16	3.99	30
L Frontal operculum (44)						-30	2	22	6.02	83
R Frontal operculum (44)						33	11	25	5.36	59
R Cingulate gyrus (24)						12	8	31	5.27	141
R Postcentral gyrus (2)						45	-25	49	3.87	44
	Tone counting and tracking									
R Calcarine sulcus (17)	15	-82	7	7.38	47					

Table 2-6. Dual-task minus single-task contrast. Coordinates are in MNI space. All results have been corrected with a p = 0.01 FDR, and a minimal cluster size of 25. All reported t-values have $p < .001$.

each ROI can be found in Table 2-7. Bayes factors[5] (BF) computed for each ROI are reported in Table 2-8 (difference from baseline) and Table 2-9 (summation of component tasks vs. dual tasks), which were used to assess the strength of evidence against the null effect.

Areas within the frontal region of the brain have been associated with dual-task performance in several studies (Collette et al., 2005; Dux et al., 2006; Erickson et al., 2005; Herath et al., 2001; Szameitat et al., 2002). The dual-task conditions of the current paradigm showed reliable activation in two frontal regions: the dorsolateral prefrontal cortex (DLPFC, Figure 2-5A and 2-5B), and the ventrolateral prefrontal cortex (VLPFC, Figure 2-5C). The DLPFC showed activity primarily related to working memory processes, as evidence for increased activation during 2-back conditions was considerable. The VLPFC seems to be involved in 2-back only: there is strong evidence for increased activation during conditions involving 2-back, while there is considerable evidence against involvement of the VLPFC during the remaining conditions. Indeed, a meta-analysis by Owen et al. (2005) indicates that the VLPFC has a strong association with the n-back task. In all frontal areas there was

[5] Interpretation of Bayes factors is straightforward: According to Jeffreys (1961, p. 432), a BF > 3 indicates substantial evidence for the alternative hypothesis, while a BF > 10 indicates strong evidence. The inverse also applies: a BF < 1/3 and a BF < 1/10 is substantial and strong evidence against the alternative hypothesis, respectively.

Region of interest	Left coordinate			Right coordinate			Note
	x_l	y_l	z_l	x_r	y_r	z_r	
STG	-60	-31	10	65	-28	9	The right hemisphere ROI is the average of the (63, -28, 7) and (65, -28, 9) maxima of Table 5.
ITG	-48	-73	-2	54	-70	-2	
IPL	-33	-43	40				
SPL	-21	-55	61				
DLPFC 9/46	-51	2	31	45	2	34	
DLPFC 10/49	-39	50	22	38	41	31	The right hemisphere ROI is the average of the (39, 44, 31) and (36, 38, 31) maxima of Table 5.
VLPFC	-33	20	4	39	20	1	
Cerebellum	-18	-55	-23	18	-55	-23	As functioning in the cerebellum is lateralized, ROIs for both hemispheres were defined, despite the dual-tasks only showing t-value peaks in the right hemisphere.
pre-SMA	-3	6	57				As the division between pre-SMA and SMA-proper is debatable, and the area was active in multiple conditions, the coordinate from a recent meta-analysis was used (Mayka et al., 2006).

Table 2-7. Definition and origin of regions of interest. When two maxima in Table 5 are in close proximity (a maximum distance of 6 for any axis in MNI space) the average of the two was taken.

strong evidence for additive activation, but not for over-additive activation.

Alongside the frontal regions, the parietal lobules have been connected to dual-task processing (Just et al., 2001; Just et al., 2008; Szameitat et al., 2006), and in the current study the dual-tasks showed significant parietal activity, both in the superior (SPL, Figure 2-5D) and inferior lobule (IPL, Figure 2-5E). The SPL was found to be active during the tracking task. The 2-back plus tracking condition seems to result in over-additive activation, but the evidence was inconclusive (Table 2-9). The activation pattern of the SPL fits with existing theories of parietal activity, which link the supraparietal lobules to visuospatial functions (Culham & Kanwisher, 2001). The IPL show strong evidence for involvement in the 2-back task, but mostly evidence against involvement for the remaining two tasks. This particular region has previously been connected to working memory (e.g., Borst & Anderson, 2013), and could therefore be required to perform the 2-back task. Activation during the dual-task conditions showed substantial evidence of being additive.

The regions mentioned thus far have been identified mainly due to over-additive activation. We are also interested in under-additive behavior, and previous studies
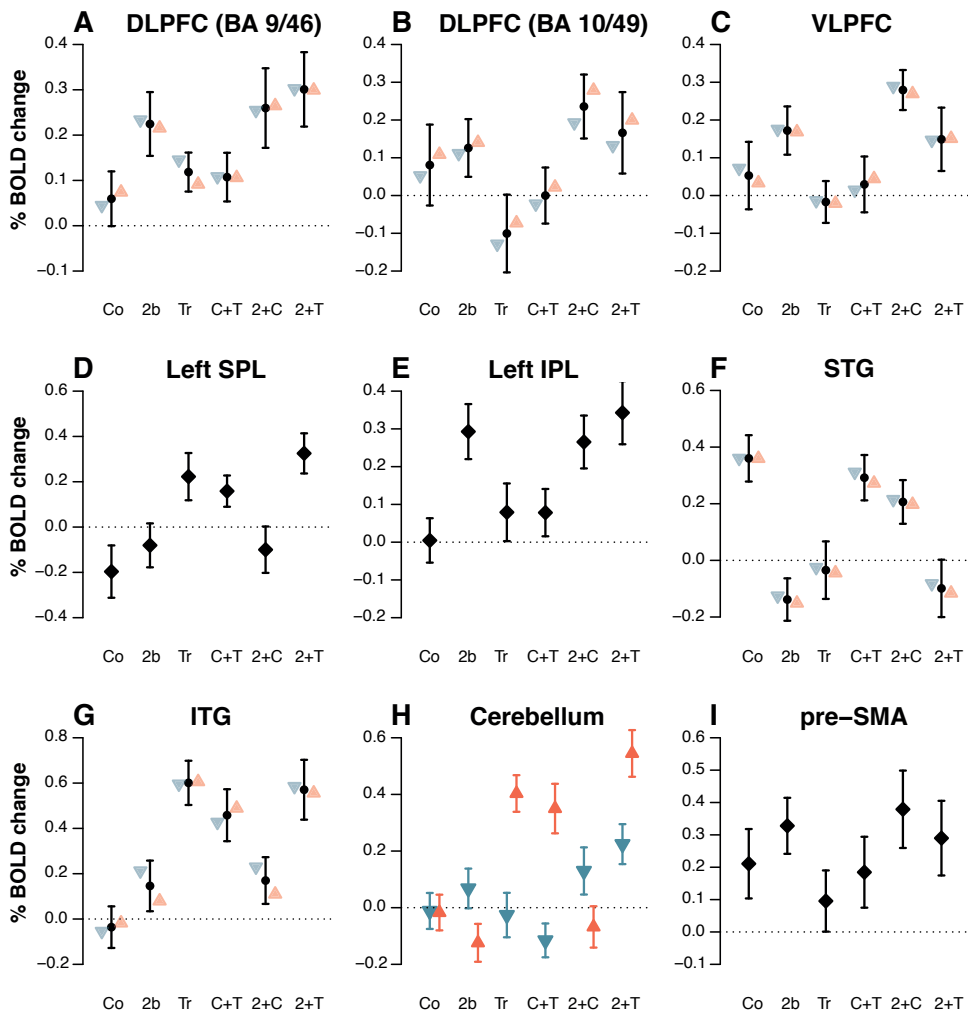
Figure 2-5. Changes in BOLD signal for different regions of interest in each condition. Red triangle: right lateralized region. Blue inverted triangle: left lateralized region. Black circle: average of left and right. Black diamond: single region. Co: tone-counting, 2b: 2-back, Tr: tracking, C+T: tone-counting plus tracking, 2+C: 2-back plus tone-counting, 2+T: 2-back plus tracking. Left and right regions have been plotted separately for regions that showed qualitatively different patterns between the two hemispheres.

have shown that under-additive activation can occur strongly in sensory regions (Buchweitz et al., 2012; Just et al., 2008). We therefore investigated the superior temporal gyrus (STG, Figure 2-5F) and inferior temporal gyrus (ITG, Figure 2-5G), which are involved in aural (Celsis et al., 1999) and visual processing (Ishai et al., 1999), respectively. Indeed, these regions showed strong activation in the current paradigm. Examining the activation pattern of the STG across conditions confirms

ROI (side)	Single tasks			Dual tasks			
	Task	BF	Evidence	Task 1	Task 2	BF	Evidence
STG	Co	4.57×105	>>>	Co	Tr	3.70×104	>>>
	2b	34.2	<<<	2b	Co	9.70×102	>>>
	Tr	0.30	==	2b	Tr	1.32	-
ITG	Co	0.32	==	Co	Tr	1.23×105	>>>
	2b	4.11	>>	2b	Co	15.2	>>>
	Tr	6.23×107	>>>	2b	Tr	35.4×105	>>>
SPL (L)	Co	19.0	<<<	Co	Tr	2.15×102	>>>
	2b	0.85	-	2b	Co	1.31	-
	Tr	1.10×102	>>>	2b	Tr	4.05×104	>>>
IPL (L)	Co	0.24	==	Co	Tr	3.31	>>
	2b	1.32×105	>>>	2b	Co	6.08×104	>>>
	Tr	1.59	-	2b	Tr	1.75×106	>>>
DLPFC 9/46	Co	1.35	-	Co	Tr	63.3	>>>
	2b	7.08×103	>>>	2b	Co	2.92×103	>>>
	Tr	1.32×103	>>>	2b	Tr	3.96×104	>>>
DLPFC 10/49	Co	0.69	-	Co	Tr	0.24	==
	2b	15.3	>>>	2b	Co	1.49×103	>>>
	Tr	1.32	-	2b	Tr	10.0	>>>
VLPFC	Co	0.46	=	Co	Tr	0.32	==
	2b	1.04×103	>>>	2b	Co	6.08×107	>>>
	Tr	0.29	==	2b	Tr	25.5	>>>
Cerebellum (L)	Co	0.25	==	Co	Tr	48.5	<<<
	2b	1.29	-	2b	Co	10.76	>>>
	Tr	0.29	==	2b	Tr	6.83×103	>>>
Cerebellum (R)	Co	0.27	==	Co	Tr	1.26×105	>>>
	2b	35.3	<<<	2b	Co	1.14	-
	Tr	7.52×107	>>>	2b	Tr	1.85×108	>>>
pre-SMA	Co	55.6	>>>	Co	Tr	17.7	>>>
	2b	6.09×104	>>>	2b	Co	6.58×103	>>>
	Tr	1.46	-	2b	Tr	5.13×102	>>>

Table 2-8. Comparing the sum of component tasks to the dual-task. A paired Bayesian t-test was performed between the summed single-tasks and the relevant dual-task. Bayes factors present evidence against the null hypothesis. Interpretation of the BF for under-additive activation: < is moderate, << is substantial, and <<< is strong evidence. Likewise, for over-additive activation: > is moderate, >> is substantial, and >>> is strong. Finally, the interpretation for additive activation: = is moderate, and == is substantial. A minus sign means that evidence was inconclusive.

its role in auditory processing, as strong evidence for activation is seen only when the tone-counting task was performed. The changes in average BOLD response seem to indicate that activity in dual tasks containing tone counting was under-additive in 2-back plus tone counting when compared to single-task tone counting. However, the evidence is substantially in favor of an additive explanation. While inconsistent with earlier studies, this is due to the deactivation seen in both the tracking and

ROI	Task1	Task2	BF	Evidence
STG	Co	Tr	0.36	=
	2b	Co	0.25	==
	2b	Tr	0.37	=
ITG	Co	Tr	0.92	-
	2b	Co	0.40	=
	2b	Tr	1.83	-
SPL (L)	Co	Tr	1.19	-
	2b	Co	3.98	>>
	2b	Tr	1.67	-
IPL (L)	Co	Tr	0.25	==
	2b	Co	0.31	==
	2b	Tr	0.27	==
DLPFC 9/46	Co	Tr	2.04	<
	2b	Co	0.28	==
	2b	Tr	0.33	==
DLPFC 10/49	Co	Tr	0.25	==
	2b	Co	0.26	==
	2b	Tr	1.72	-
VLPFC	Co	Tr	0.24	==
	2b	Co	0.38	=
	2b	Tr	0.24	==
Cerebellum (L)	Co	Tr	0.80	-
	2b	Co	0.69	-
	2b	Tr	10.1	>>>
Cerebellum (R)	Co	Tr	0.34	=
	2b	Co	0.76	-
	2b	Tr	1.91×10^2	>>>
pre-SMA	Co	Tr	4.90	<<
	2b	Co	14.1	<<<
	2b	Tr	4.47	<<

Table 2-9. Comparing the sum of component tasks to the dual-task. A paired Bayesian t-test was performed between the summed single-tasks and the relevant dual-task. Bayes factors present evidence against the null hypothesis. Interpretation of the BF for under-additive activation: < is moderate, << is substantial, and <<< is strong evidence. Likewise, for over-additive activation: > is moderate, >> is substantial, and >>> is strong. Finally, the interpretation for additive activation: = is moderate, and == is substantial. A minus sign means that evidence was inconclusive.

2-back single-tasks that, when summed with tone-counting, results in an additive effect. The ITG follows a pattern very similar to the SPL, and likewise showed strong evidence for an increase in activation during conditions that included tracking or 2-back. Again, activity found in the dual tasks seems additive for this region, although the evidence is not very strong.

All ROIs discussed above were located in the cortex. However, the cerebellum

(Figure 2-5H) has been argued to be involved in dual-tasking as well (Wu et al., 2013). Of all ROIs, the cerebellum showed the largest differences between the left and right regions. This is not surprising given its lateralized role in motor function. Activation in the right-sided cerebellum region increased exclusively in the tracking task, for which evidence is strong. The left-sided region showed activation related to the 2-back task, although the evidence was only substantial for dual-tasks involving 2-back, and not the single-task. Both left- and right-sided regions showed strong evidence for over-additive activation in the 2-back plus tracking condition.

Finally, there are some indications that the pre-SMA is involved in dual-tasking (Marois et al., 2006). Indeed, upon visual inspection (Figure 2-3), the area containing the approximate location of the pre-SMA indicates activity during all conditions. Figure 2-5I shows that especially the 2-back and tone-counting tasks cause large increases in activation. Evidence for activation during these WM tasks was strong, while evidence for activity during tracking was only equivocal. The dual tasks involving 2-back displayed the highest activation, and dual-tasks activation presented strong evidence for being under-additive compared to the single tasks.

In summary, none of our ROIs showed evidence for over-additive activation in all three dual tasks. Of the ROIs, only the pre-SMA demonstrated under-additive behavior during dual-task conditions. In contrast, the cerebellum showed over-additive activation for the 2-back plus tracking condition. Finally, the sensory and prefrontal regions showed considerable evidence for additive activation during dual tasks.

To make sure that we did not miss any regions showing over-additive activation in all three dual tasks due to our ROI-selection procedure, we performed the same analyses on ROIs around the remaining dual-task cluster maxima in Table 2-5 and around the single-task cluster maxima of Table 2-4. These analyses yielded very similar results as the ones discussed above; none of the additional ROIs showed over-additive activation in all three dual-tasks. We report the results in detail in the Supplementary Material.

Single-task Overlap and Dual-task Accuracy

In the introduction we hypothesized that dual-task interference is caused by an overlap in resource use of the component tasks. If single-task activation is an indication of which resources are used for a particular task, overlap in activation between single tasks should be predictive of dual-task interference. A seemingly straightforward way to compute the overlap between activation in two conditions is to count the number of active voxels in the intersection of two maps (e.g., Herath et al., 2001). However, there are two concerns with this method. First, the voxel count is dependent on the chosen statistical threshold (see Nieuwenhuis et al., 2011). Second, because this computation requires a binary representation of activity, voxels that have relatively low reliability (that is, they barely exceed the activation threshold) have equal weight to voxels that have high reliability. This could lead to an overestimation
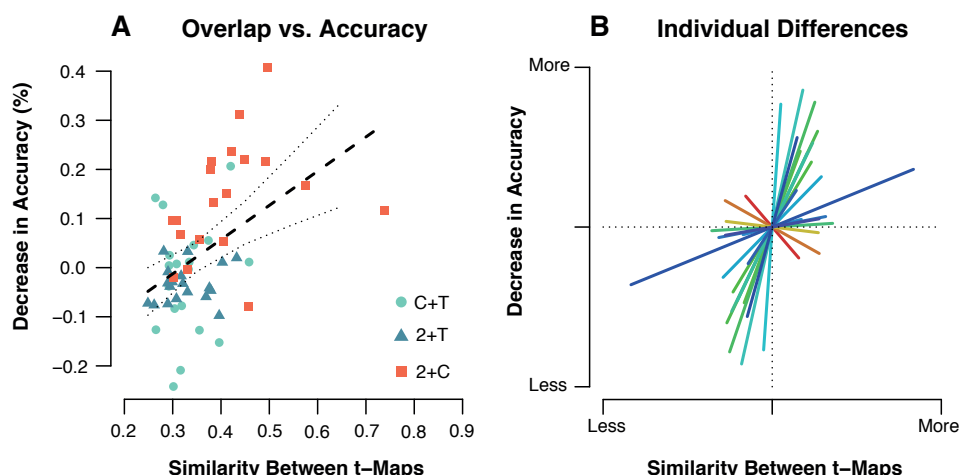
Figure 2-6. *Panel A:* Correlation between single-task similarity and accuracy decrease when the two tasks are combined. 95% CI plotted as dotted lines (Chambers & Hastie, 1992). C+T: counting with tracking, 2+T: 2-back with tracking, 2+C: 2-back with counting. *Panel B:* Each line is a single-subject regression slope between single-task t-map similarity and accuracy decrease. Lines with warm colors have a negative slope, while lines with cool colors have a positive slope. Participants with positive slopes show lower accuracy when similarity is higher. All slopes have been centered for clarity, and the length of the each line indicates the range of values found for that participant.

of the overlap between conditions. Essentially, this voxel-counting approach throws away information that could be useful in computing the similarity between voxel maps. In order to ameliorate this issue, we propose a modification to this method that can handle continuous values, while still resulting in the correct evaluation of overlap for the binary case. As such, this approach is a generalization of the voxel-counting method.

The inputs of the similarity computation are the t-maps (as produced by SPM) for each pair of single tasks at the subject level. The t-values were chosen because they contain information on the strength and reliability of the activation in a particular voxel, for a certain condition. All voxels with $t < 0$ are set to 0. Thus, all evidence for activation is taken into account, and the concern of using an arbitrary threshold is addressed. The calculation used to determine the similarity between the two resulting t-maps is $1/(1+d)$ where d is the Euclidian distance between the t-values of two voxel maps in n-dimensional space, with n being the number of voxels in the map. The use of this distance measure addressed the concern of voxel weight.

The similarity between two single-task conditions was compared to the average decrease in accuracy observed in the dual-task condition. This decrease was computed as $(T1_{dual} - T1_{single} + T2_{dual} - T2_{single})/2$, where $T1_{single}$ is the average single-task accuracy for the first task found in the dual-task, and $T1_{dual}$ is the average accuracy for the

same task during the dual-task condition. T2 denotes the second component task of the dual-task. In Figure 2-6A this decrease in dual-task accuracy is plotted against single-task similarity for each participant. Counting plus tracking showed the lowest similarities, whereas 2-back plus tone-counting showed the highest similarities. This is mirrored by the accuracy decrease, which was the smallest in counting plus tracking, and the highest in 2-back plus tone-counting. To test the significance of this relationship, we computed the correlation between similarity and accuracy loss over all three dual-tasks within each subject. A Fisher r-to-z transform[6] was applied to the correlation coefficients, and a one-sample t-test was applied to the resulting z-scores. The relationship was significant ($t(18) = 4.50$, $p < .001$) and showed a strong correlation ($r = .47$, $p < .001$).

One might be tempted to evaluate the relationship between similarity and accuracy decrease within each dual-task condition. In that light, it seems the effect is mostly driven by the 2-back plus tone-counting condition. However, the correlation within each dual-task can be misleading, as it is measured across participants. Some participants may show a stronger on-task effect, which could lead to a higher degree of similarity between tasks. Put differently, participants might be performing a task in different ways from each other, which makes it difficult to compare their brain activity directly in terms of similarity. However, to better understand the result of Figure 2-6A, we can look at the relationship between both variables within participants. To that end, we plotted the individual regression slopes for the similarity vs. accuracy correlation in Figure 2-6B. Overall, the slopes were significantly different from zero ($t(18) = 2.60$, $p = .018$): Most participants ($n = 16$) show a positive slope between similarity and accuracy decrease. This means that accuracy was lower when the similarity between t-maps was higher, which is consistent with the findings of Figure 2-6A.

Discussion

At the start of this article we hypothesized that brain activation in response to multitasking is dependent on the particular tasks that are used, instead of indicating a multitasking locus. This idea was based on recent behavioral theories on multitasking which assume that multitasking interference is a result of overlapping resource use (Meyer & Kieras, 1997; Salvucci & Taatgen, 2008, 2011; Wickens, 2002) and on the diverging results of fMRI multitasking studies (Adcock et al., 2000; Just et al., 2001; Szameitat et al., 2002). In the current experiment we found no indication of regions that correlated exclusively with dual-task performance in all three dual tasks. Instead, we found a mix of under-additive, additive and over-additive activation in different areas, which is in line with the idea that multitasking activation and interference are dependent on the tasks.

If it is true that single-task resource requirements determine multitasking interference and if single-task activation is an index of resource use, the overlap in

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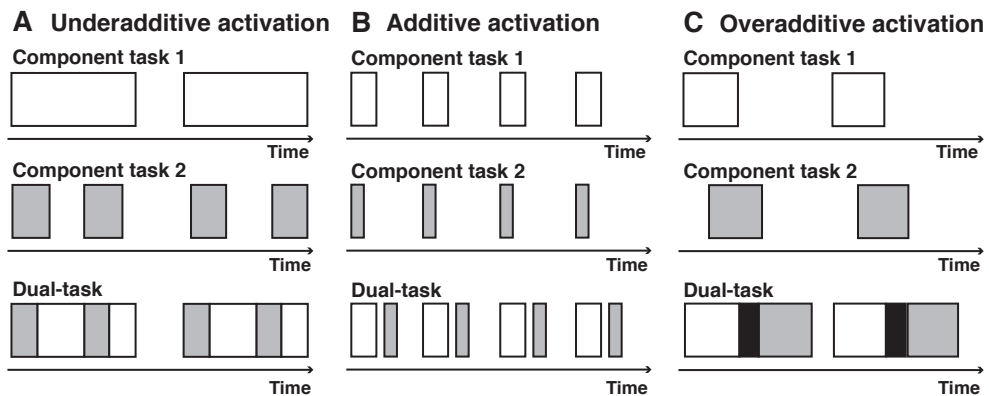[6] Required because Pearson's r is not distributed normally.

Figure 2-7. Illustration of all three types of additive activation. The blocks represent activity in a certain region. White signals activity for task 1, grey is for task 2, and black represent additional activity not inherent to either task 1 or 2.

single-task activation between two tasks should be predictive of dual-task interference. In the current experiment we did indeed find a strong correlation between single-task activation similarity and accuracy decrease in the corresponding dual task. Hence, the neuroimaging findings complement the idea of the recent behavioral theories that a higher degree of resource contention between tasks leads to lower performance: dual-task accuracy decreases as similarity in activated regions (resources) between single-tasks increases.

Although the general pattern of the results seems to be in favor of our hypothesis, the question remains whether such a framework can explain the details of the current results, as well as the divergent results in the literature. In the remainder of this discussion we will explore these issues in some detail.

Differences in Activation Found During Multitasking

In the current study we found a combination over-additive, additive, and under-additive results. If the observed activation patterns are a result of task interactions, it should be possible to explain the different types of dual-task activity based on the properties of the component single tasks.

Under-additive Activation

Anderson et al. (2011) hypothesized that under-additive activation occurs when resource competition between tasks leads to one process (or task) taking away resource time from another process (time sharing), resulting in a smaller net increase in activation (see Figure 2-7A). In the current study indications of under-additive activation are primarily seen in areas used by just one of the tasks. Time sharing can account for this, as all time has to be shared between tasks: resources required by a

single task can thus be accessed less frequently, leading to a smaller gain in activation.

For example, the superior temporal gyrus (Figure 2-5F) shows a drop in activation from single-task tone-counting to either of the relevant dual tasks. As this area is part of the primary auditory cortex, we can assume that it is used only to process the tones. A time-sharing account predicts the decrease because there is less time available for auditory processing in the dual task conditions than in the single task condition (note that the duration of the complete task was fixed in our experiment). In a similar fashion, the supraparietal lobule (Figure 2-5D) and the inferior temporal gyrus (Figure 2-5G) show slight drops in activity when comparing the tracking single task to the tone-counting plus tracking condition. Time sharing can also be used to explain these drops, as the SPL is involved in visual-spatial processes (Culham & Kanwisher, 2001), while the ITG plays a role in visual processing (Ishai et. al., 1999). Both of these would be required for tracking, but play no role in tone-counting, and only a small role in 2-back. Therefore, if the dual task results in less time being allocated to tracking, a decrease in activity should occur.

Under-additive activation was also found in the pre-SMA area (Figure 2-5I). The pre-SMA has been linked to inhibition and switching behavior (Obeso et al., 2013). Its role in switching would fit the activation seen in dual-task conditions, but does not explain activation during single tasks. Another possibility for the involvement of the pre-SMA is sub-vocal rehearsal, to which it has been linked previously (Awh et al., 1996; Koelsch et al., 2009; Marvel & Desmond, 2010). Additional support for the use of rehearsal strategies comes from the activation in the premotor cortex for both tone-counting and 2-back (Figure 2-3A and 2-3B): the premotor cortex has also been implicated in sub-vocal rehearsal (Awh et al., 1996; Henson et al., 2000; Koelsch et al., 2009). The rehearsal explanation fits best with the observed differences in activation: if rehearsal is performed during both 2-back and tone counting, one process takes away some rehearsal time from the other, resulting in a smaller net increase. Still, none of these accounts explain why the pre-SMA area shows some activity in the tracking task. However, the center of SMA activity during tracking appears to be centered more on the SMA-proper (Figure 2-3B), which is engaged in motor tasks (Hoshi & Tanji, 2004). As the division between SMA-proper and pre-SMA is not strictly defined (Mayka et al., 2006), it could be some motor activity has been 'mislabeled' as pre-SMA activation.

Additive Activation

Additive effects can also be explained by a time-sharing account, if we assume that access to resources has been integrated perfectly between two processes and one process does not take away time from the other (Salvucci & Taatgen, 2008; Schumacher et al., 2001). Thus, the net activation would be the summation of activation caused by each process (see Figure 2-7B).

Additive behavior presented itself in frontal regions such as the DLPFC (Figure 2-5A and 5B) and VLPFC (Figure 2-5C). The DLPFC is associated with declarative

memory (Anderson et al., 2008; Borst & Anderson, 2013; Olesen et al., 2004), while the left VLPFC has been implied in the cognitive control of memory (Badre & Wagner, 2007). Furthermore, the right VLPFC has been associated with numerous functions, such as motor inhibition and action updating (Levy & Wagner, 2011). Additive behavior would imply efficient integration between tasks for these regions. In turn, that would indicate that either component task does not tax these regions continuously. As tone counting and 2-back both have time between subsequent stimuli, the tasks are not continuous, and processing primarily occurs at discrete intervals. Therefore, it is plausible that these regions are not used continuously while processing these tasks. For example, if the amount of information retrieved during the dual task is the sum of what is retrieved during the single tasks, we would expect additive behavior in the DLPFC: retrieving information from declarative memory is not a continuous process, and only required at the presentation of a new stimulus. Therefore it is likely to be integrated efficiently between tasks.

Over-additive Activation

Over-additive effects can be explained by assuming that the performance of the dual-task consists of more than the sum of its component tasks, such that resources handle additional processes not found in either component task (see Figure 2-7C). This seems to be the case in the 2-back plus tracking condition, which adds a new process to the task in order to manage the switching of attention between two screen areas, as well as switching between hands for the correct input. Thus, this attention-switching process only occurs in the dual-task, leading to an over-additive effect on activation (for a parallel of this in the sequential multitasking domain, see Borst, Taatgen, Stocco, et al., 2010; Borst et al., 2011).

 Over-additive activation was found primarily in the cerebellum (Figure 2-5H). The cerebellum is important for visuomotor control (Stoodley & Schmahmann, 2009). This is consistent with the hypothesis that the extra activation during 2-back plus tracking could be explained as additional demands on both visual and motor processes. In more general terms, a time-sharing account can explain why surplus activity was found in visual areas of all dual-tasks (Figure 2-4): as time is taken away from a visual task, the chance of errors for that task increase, as does the effort (and resources), required to avoid those errors. For example, finding the tracking target might require more work because it has moved a greater distance from its previous location. Likewise, processing a 2-back letter might need to be done in less time, because the letter was already on the screen for some time before attention shifted to the 2-back task, and is at risk of disappearing at any moment.

Multitasking Activation Differences in the Literature

Our account should also be able to explain the differences observed in the literature. For example, the under-additive activation encountered by Just et al. (2008) was located primarily in areas related to visual processing when driving was combined

with an auditory task. The reduction in activity compared to the driving single task could be explained by time sharing between tasks, resulting in a smaller net activation. In contrast to the results found by Just et al., Adcock et al. (2000) found additive activity in a dual-task containing a visual and auditory task. The difference is that neither task in the Adcock et al. (2000) study required continuous processing, unlike a driving task. Therefore, it is likely that the tasks could be integrated much better, with one task not taking away time from the other.

Sometimes the same task can show different types of additive behavior. For example, Jaeggi et al. (2003) tested three variations of the n-back task in a dual-task setting. The results showed mostly additive activation for the dual 1-back and dual 2-back conditions, but strong under-additive activation in the dual 3-back. A time-sharing explanation would be that the memory load (i.e., declarative processing) is low enough to be interleaved perfectly in the dual 1-back and dual 2-back conditions. However, during the dual 3-back the increased load results in processing times that can no longer be interleaved within the available time, which results in one n-back taking time away from the other n-back.

In PRP designs, the dual task is usually found to produce over-additive activation. This would indicate additional processing stages: a new action that must be performed which was not a part of the component tasks. Often these processes are attributed to a dual-task specific region or functionality (Collette et al., 2005; Szameitat et al., 2002). However, there are indications that these extra processes are an artifact for this particular task; e.g., a strategy of active inhibition of response to the second stimulus (Salvucci & Taatgen, 2008; Schumacher et al., 2001), or switching of response rules from stimulus one to stimulus two (Kiesel et al., 2010). The fact that only a fraction of dual-task studies show dual-task specific areas further supports this notion. In contrast to PRP designs, more complicated dual-task settings often show additive and under-additive activation in dual-tasks. Given that more complicated tasks have a higher likelihood of contention for resources, the current account of dual-task activation would predict these results. Indeed, if there were a multitasking locus, one would expect to find such a region especially in more complicated dual-task settings.

In addition to explaining the observed BOLD responses found in dual-tasks literature, the time-sharing account also fits well with the accompanying behavioral data. It predicts that under-additive and over-additive activation during the dual-task is accompanied by reductions in performance, due to less time-on-task and additional task requirements, respectively. This is clearly supported by the literature (e.g., Buchweitz et al., 2012; Dux et al., 2006; Just et al., 2008; Szameitat et al., 2002). The prediction for additive activation is different, however: as both tasks can be integrated perfectly in this situation, there should be no decrease in component-task performance during the dual task. This is supported by the literature as well: the results of both Adock et al. (2000) and Jaeggi et al. (2003) showed almost no decrease in performance for conditions where the activation was additive.

Different types of activation (under-additive in particular) have also been

explained as a capacity limit for activation (Just et al., 2001). This constraint would cause a division of activation when multiple processes are performed concurrently. Over-additive activation is then explained as task switching during simple tasks, which does not reach the total limit. Indeed, the capacity limit theory (formalized in 4CAPS; see Just & Varma, 2007) is very similar to our time-sharing account (formalized in threaded cognition; see Salvucci & Taatgen, 2008), and both should produce comparable predictions for activation. The main difference is that time-sharing only imposes local (resource or region based) limits on activation, but no global limit. Therefore, we believe the time-sharing mechanism provides a more parsimonious account of the current data. Furthermore, we have shown that a time-sharing account can readily account for over-additive activation in complex, continuous tasks (e.g., when tracking is combined with 2-back). Also note-worthy is that time-sharing can be extended to explain training effects seen in multitasking settings (Dux et al., 2009; Erickson et al., 2007). In these studies, a drop in activation is seen after a task has been extensively trained. To explain this, we assume that task related processes could be expressed in terms of decision rules, each of which has a fixed execution time. After initial learning, a task would be comprised mainly of simple rules, representing declarative knowledge of the task. Through practice, these simple rules could combine into more complex, proceduralized, rules (for details, see Taatgen & Lee, 2003). This causes two optimizations: fewer rules need to be executed to perform a task, and many intermediate results (e.g., memory retrievals for declarative knowledge) can be omitted. Both of these optimizations lead to lower time-on-task, which would mean less resource use over a given time-span, and thus lower levels of activation.

Conclusion

In this study we performed an fMRI experiment to investigate whether multitasking interference depends on resource overlap. The results indicated that the observed activation patterns were caused by interactions between tasks, instead of specific multitasking functionality of the brain. In addition, it was shown that similarity, and thus overlap, in cortical activity patterns of component single-tasks correlated with performance decreases in dual-tasks. Furthermore, diverging results found in the literature could be explained by task interactions as well: a combination of time sharing between tasks and additional processing stages found only in certain task combinations can explain under-additive, additive, and over-additive activation in dual-tasks. To conclude, no evidence of a multitasking locus was found. In the context of the current study, as well as the existing literature, it appears that the specific patterns of performance and cortical activation are a function of the specific tasks that are combined, instead of evidence for a specialized multitasking mechanism.