How to test for dual-task specific effects in brain imaging studies – An evaluation of potential analysis methods

André J. Szameitat(*), Torsten Schubert, Hermann J. Müller

Department of Psychology, Ludwig Maximilians University, Munich, Germany

(*) Address for correspondence
Dr André J. Szameitat
Department of Psychology
Ludwig Maximilians University
Leopoldstrasse 13
80802 Munich
Germany

email: szameitat@psy.lmu.de
phone: 0049-(0)89-2180-6778
fax: 0049-(0)89-2180-4866

Abstract
The study of the concurrent performance of two tasks allows deep insights into the human cognitive system and, accordingly, an increasing number of brain imaging studies are conducted to identify the neuroanatomical correlates of such dual-task performance. In this overview we present currently used approaches to identify dual-task specific activations in fMRI and PET studies. A comparison is made in order to identify the approaches which have the potential to validly detect dual-task specific activation patterns, i.e. activation which cannot be explained by the individual performance of the component tasks alone. We demonstrate that while all approaches suffer from at least some drawbacks, the best (although potentially over-conservative) approach is to compare the dual task with the sum of the single tasks, the second-best is an interaction contrast, and the third-best a conjunction analysis. Comparisons of the dual task with the mean of single-task activity or with only one single task should be avoided except for a few specific situations. We generalize our conclusions to related research areas, such as multisensory integration or divided attention.

Full reference (as of Oct 2010)

Szameitat AJ, Schubert T, Müller HJ. (in press). How to test for dual-task specific effects in brain imaging studies – An evaluation of potential analysis methods. *NeuroImage, Epub ahead of print*, doi:10.1016/j.neuroimage.2010.07.069

For a reprint of the final pdf as published in the journal, please do not hesitate to contact szameitat@psy.lmu.de

Figures and tables can be found at the end of the manuscript.

Introduction

The study of dual-task performance (i.e., the concurrent performance of two tasks) has received a wide interest in cognitive neuroscience as it provides detailed insights into the architecture of the human cognitive system. Thus, for example, dual-task paradigms have provided one of the principal approaches for investigating the central-executive component of working memory (Baddeley, 1990; D'Esposito et al., 1995). And they have been used to reveal the workings of the central attentional bottleneck in the human cognitive system (Pashler, 1994; Schubert, 2008), which is assumed to limit our ability to make choice response decisions to one at a time (Telford, 1931; Welford, 1952). Due to this central role for understanding human cognition, a considerable number of brain imaging (mainly functional magnetic resonance imaging, fMRI) studies have been conducted to investigate the neural correlates of dual-task processing (for a review, see Marois & Ivanoff, 2005).

Previous studies employed various research questions. While many studies focused mainly on the mere identification of neural activity associated with dual-task processing (Dux et al., 2006; Erickson et al., 2005; Herath et al., 2001; Hsieh et al., 2009; Jiang et al., 2004; Schubert & Szameitat, 2003; Szameitat et al., 2002), other research focused more specifically on the identification of cortical areas which are activated exclusively in the dual-task but not in the single-task situation (Adcock et al., 2000; Bunge et al., 2000; D'Esposito et al., 1995; Klingberg, 1998; Smith et al., 2001). In addition, a number of further research questions have been followed, such as testing for functional connectivity in dual-task processing (Dux et al., 2009; Stelzel et al., 2009), the effect of training (Dux et al., 2009; Erickson et al., 2007), or the effect of the amount of cortical overlap of the single-tasks on dual-task performance (Just et al., 2001; Just et al., 2008; Klingberg, 1998; Klingberg & Roland, 1997). Thus, a large number of studies on a variety of different research questions investigated the functional neuroanatomical correlates of dual-task processing.

This variety of research questions and, consequently, applied methodological approaches is reflected in the conclusions of these studies, which also cover a wide spectrum. Some studies concluded that there is evidence for neural activity associated with dual-task performance (D'Esposito et al., 1995; Dux et al., 2006; Erickson et al., 2005; Goldberg et al., 1998; Herath et al., 2001; Hsieh et al., 2009; Jiang, 2004; Koechlin et al., 1999; Schubert & Szameitat, 2003; Sigman & Dehaene, 2008; Stelzel et al., 2009; Szameitat et al., 2006; Szameitat et al., 2002), others concluded that there are no specific neural correlates of dual-task performance (Adcock et al., 2000; Bunge et al., 2000; Jiang et al., 2004; Klingberg, 1998; Smith et al., 2001), and sometimes even reduced neural activity associated with dual-task performance was reported (Jaeggi et al., 2003; Just et al., 2001; Just et al., 2008). While there are numerous potential reasons for these divergent findings, we would like to focus on one particular aspect, namely the analysis strategy of dual-task brain imaging studies.

The analysis of dual-task brain imaging research involves a number of potential complications which have to be considered carefully. One such complication arises from the fact that the absolute values of the data obtained by means of fMRI or PET (positron emission tomography) cannot be interpreted directly, so that researchers have to resort to relative values obtained by comparing (i.e., contrasting) the activity during dual-task performance with some reference activity level. Hitherto, different types of contrasts have been used for this purpose, though it is unclear how these compare in the identification of dual-task specific effects. Usually, dual-task activity is compared with activity derived from the single-task components that make up the dual task. For instance, dual-task activity may be contrasted with the activity of one single task, with the sum of both single tasks, or with the mean of the two single tasks. An alternative approach is to compare the dual task with a (resting) baseline condition. Critically, the inferences which can be drawn from such comparisons depend on the exact nature of the contrast examined. The aim of the present paper is it to discuss the various contrasts and the respective inferences that can be drawn from them so that future research can employ data-analysis and interpretation strategies appropriate for the investigated research question.

For this, we will first define potential research issues in dual-task studies, since their exact nature determines the appropriateness of an analysis method. Then we evaluate different contrasts in terms of their ability to (a) identify dual-task specific effects while (b) being immune to dual-task unspecific effects. To aid this evaluation, we will use hypothetical activation profiles of brain areas and hypothetical numerical calculations. We conclude with a recommendation which contrast performs best under specific circumstances.

Potential research questions in dual-task brain imaging research

At least two kinds of research questions can be distinguished in dual-task research, general questions and more specific ones.

We define *general research questions* as “Which brain areas do show activity at all during dual-task performance?”. For questions of this type, a comparison with a low-level baseline, such as a resting baseline (BASE), seems appropriate. [Footnote: In case of an event-related design, such a baseline condition may be implemented by the inclusion of null-events. Note that all arguments in this manuscript hold for event-related and blocked designs alike.] For instance, let us assume for the present purposes that we have a dual task which consists of two choice reaction tasks, an auditory and a visual one. In the auditory task (AUD), participants press an appropriate response button with their left hand depending on whether a target sound had a high or a low pitch. In the visual task (VIS), participants press an appropriate button with the right hand depending on whether a (visually presented) target face is that of a male or of a female. In the dual task (DT), both tasks (VIS and AUD) are presented simultaneously and participants respond to both stimuli as fast as possible. If such a dual task is compared to a resting baseline (contrast DT – BASE), one would expect neural activations at least at the level of the visual, auditory, and motor cortices. In the context of the general research question, one would conclude that these areas are involved in dual-task performance.

The fact that these areas are presumably also activated during performance of the single tasks is irrelevant for this general research question. Furthermore, it is irrelevant whether the activation in the dual task is just the sum of the single-task activations. For instance, assuming that the auditory single task does not affect visual-cortex activity, the activity in the visual cortex may be identical in the dual task and the visual single task. In other words, the activity in the visual cortex during dual-task performance would be the sum of the activity in the visual and the auditory single tasks. Thus, in the general research question activation associated with the dual task may actually be associated solely with one or both single tasks. However, since most previous brain imaging research aimed at finding effects which are specific to the dual task and which cannot be explained by the single tasks, they addressed not a general, but rather a more specific research question.

In the present manuscript, we define such a *specific research question* as "Which brain areas show dual-task specific activity?". Since a dual task can be considered as being composed of two single tasks, one may ask whether the brain activity during the dual task is either equivalent to the sum of the single tasks, or – as Duncan (1979) has put it – whether the whole (the DT) is more than the sum of its parts (the single tasks AUD and VIS). Alternatively, one may ask whether the whole is less than the sum of its parts. These questions are aimed at identifying what is specific to the dual-task performance relative to the single-task performance. In other words, is there a change in neural activity which cannot be accounted for (or predicted) by the single tasks?

Let us reconsider the above example of visual-cortex activity under the assumption of a specific research question: As described above, the visual cortex activity in the dual task is identical to the summed activities of the single tasks. Thus, it is neither more or less than the sum of the activation in the single tasks and, accordingly, it is not specific to the dual-task situation. Consequently, in the context of the specific research question, we would conclude that this area is *dual-task-unrelated*.

An alternative finding might have been that the visual cortex is less active during the dual task as compared to the visual single task, since attention is divided among the visual and auditory modalities (cf. Just et al., 2001). Since the dual task in this case shows activity significantly different from the sum of the single tasks, it is a *dual-task-specific* effect. Another example of a dual-task-specific effect would be an activation in the dual task which was not present in either single task (e.g. D'Esposito et al., 1995; Schubert & Szameitat, 2003; Szameitat et al., 2002). These examples demonstrate that in the specific research question, we look for effects which are not expected based on what we know from the single-task performance. Brain areas showing such effects would be referred to as "dual-task-related" or "being involved in dual-task performance", but they could also be termed "dual-task-specific", as we will do in the remainder of the paper.

Taken together, we propose that when looking for dual-task-*specific* effects, as virtually all previous studies did, a specific research question should be pursued. Accordingly, we will elaborate how to analyze dual-task brain imaging studies in the context of the specific research question.

Comparison of contrasts for testing for dual-task specific effects

As set out in the last section, in the context of the specific research question, if we are interested in an activity change caused specifically by the dual-task situation, we have to rule out that the activity change is caused by one or both single tasks. To test whether several previously employed contrasts can accomplish this, we will create a framework consisting of three elements: First, we will propose brain areas with hypothetical activation profiles. Importantly, some areas will show dual-task-specific effects, while others will not. Second, we will conduct a task analysis. For this, we will define which sources (e.g., auditory stimulation, visual stimulation, dual-task-specific effects) may contribute to the activity in the different task conditions BASE, AUD, VIS, and DT. Third, by combining the first two steps, we will predict the activations which the hypothetical areas would be expected to show in each task. These predicted activations will provide the basis for testing whether the contrasts will accurately identify dual-task-specific effects.

Step 1: Hypothetical activation profiles

For the present discussion, let us assume six hypothetical brain areas with distinct types of activation profiles (Table 1): The first area (hereafter named Area-V) responds only to visual stimulation. Thus, it is activated in the visual single task VIS, but not in the auditory task AUD. Since the visual stimulation is the same during the dual task and the visual single task, the activity in this area is identical in the two conditions DT and VIS. This means that the activity is independent of whether the visual stimulation is in the context of a single or a dual task (in the remainder, we will term this "dual-task-unrelated"). The second area (Area-A) responds only to auditory stimulation. Thus, it is activated in the auditory single task AUD, but not in the visual task VIS. Since the auditory stimulation is the same in AUD and DT, activity is the same in both conditions. This means, Area-A is dual-task-unrelated. The third area (Area-AV) responds to visual and auditory stimulation. Thus, it is activated in the conditions AUD, VIS, and DT. Activity in the dual task is identical to the sum of the activities in AUD and VIS (DT = AUD + VIS). Thus, activity of the single tasks is additive and there is no dual-task-specific effect, that is, this area is dual-task-unrelated. The fourth area (Area-AVD) also responds to auditory and visual stimulation, that is, it is activated in conditions AUD, VIS, and DT. However, in contrast to Area-AV, there is an additional over-additive dual-task-specific effect: activity in Area-AVD is significantly higher than predicted by the sum of the single tasks (DT > AUD + VIS). The fifth area (Area-MAVD) is like Area-AVD: it responds to auditory and visual stimulation and there is a dual-task-specific effect. In addition, let us assume (for reasons which will become apparent later; see Contrast 5) that this area shows activity during the resting baseline beyond the usual resting activity. Finally, the sixth area (Area-D) responds only to the dual-task situation, but not to the visual or auditory stimulation. Thus, it is activated only in DT, but neither in AUD nor in VIS. (See Table

2 for further hypothetical types of activation profiles which are not discussed in the text.)

We defined this set of areas because it will aid the evaluation of the contrasts. In the context of the specific research question, we are looking for a contrast which will identify the dual-task-specific effects in Area-AVD, Area-MAVD, and Area-D, while ensuring that it will not erroneously show activation in Area-A, Area-V, or Area-AV.

Step 2: Task analysis

After the definition of hypothetical areas, we turn to a detailed analysis of the sources of activity in the different tasks (Figure 1). Generally, let us first assume that the activity of a brain area elicited by a task can be separated into two components: a task-specific component and a task-unspecific component (Gusnard & Raichle, 2001). The task-specific component is the activity caused by the experimental manipulation, for example, the increase of activity in auditory areas in response to auditory stimulation. The task-unspecific component reflects a base rate of neural activity which is constant in a particular area under all conditions. This unspecific component may be estimated by a resting baseline condition (Gusnard & Raichle, 2001). Thus, if a brain area is at rest and then activated by a task, the activity starts from the task-unspecific activity level and rises by the amount of the task-specific effect.

Given this assumption, let us now consider the underlying components of the activity in the different task conditions: In a resting baseline condition (BASE), typically only the task-unspecific component (denoted "u") is present. In the auditory single-task AUD, the task-unspecific component u is present and the task-specific component related to AUD (denoted "A"). In the visual single task, u and the VIS-specific task component ("V") are present. In the dual task, the unspecific component u, the single-task components A and V, as well as a dual-task-specific component (denoted "D") are present (Figure 1).

Step 3: Predicting activation patterns for each area

Next, we will combine Steps 1 and 2, so that we can determine for each hypothetical area which activity components are present in the different tasks. For instance, Area-AV is activated by auditory and visual stimulation in an additive, that is, dual-task-unrelated manner. Under the different task conditions, this area will show the following activation patterns: During the baseline condition BASE, we expect in this area activity related to the task-unspecific component u. During the visual single-task VIS, we expect the unspecific component u and the component associated with visual stimulation V. Correspondingly, in the auditory single task, we expect activity consisting of u and A. Finally, in the dual task, the observed activity consists of u, A, and V. As another example, in Area-AVD, which is identical to Area-AV except for the additional dual-task-specific effect D, we expect a similar pattern: u during BASE, u and A during AUD, and u and V during VIS. The DT condition differs, however, in that the activity now is expected to consist of u, A, V, and D. Please refer to Table 1 (part A) and Table 2 (part B) for a comprehensive description of all hypothetical areas.

Evaluating the contrasts

Finally, we will use the predicted activation patterns to evaluate which contrasts are able to validly identify dual-task-*specific* activation. For this, a contrast must fulfill a simple criterion: If the contrast reveals activation, it should be solely related to the dual-task-specific component D. Accordingly, such a contrast should show activations only in Areas-D, -AVD, and -MAVD, but never in Areas-A, -V, or -AV. For instance, the contrast DT-BASE would identify all hypothetical areas as being activated, which renders it unsuitable for testing for dual-task-specific effects. In addition, the activity in, for instance, Area-AVD produced by the contrast DT-BASE would not be solely due to the dual-task-specific component D, but may also be caused by single-task activities (A and/or V). To illustrate this, let us use a more formal notation in which we can describe the contrast as (DT) – (BASE) as (u,A,V,D) – (u) which results in (A,V,D).

In the following, six different contrasts will be evaluated according to these criteria (cf. Table 1 (part B) and Table 2 (part C)). In addition, if appropriate we will discuss further considerations and pitfalls associated with each contrast.

It is important to note that the following evaluation of the contrasts is based on the assumption of linearity. In other words, we assume that the activity evoked by the two single tasks adds linearly, and that any departure from linearity (i.e., over-additive or under-additive effects) is an indication of dual-task-specific effects. While nonlinear effects are conceivable (see Discussion), they are beyond the scope of the present paper.

Contrast 1: DT – Baseline

As mentioned above, the activity in the dual-task condition may be caused by the auditory component task, the visual component task, the dual-task situation, or the task-unspecific component. Because we subtract only the task-unspecific component in this contrast, an observed activation may be due to any component except the task-unspecific one. In other words, if we observe an activation, we cannot decide whether it is related to A, V, or D (Tables 1 and 2). Therefore, the contrast DT-BASE is not suitable for testing for dual-task-specific activations.

Contrast 2: DT – One single task

Another conceivable contrast is to subtract one single task from the dual task, that is, DT-VIS or DT-AUD. However, the dual task consists of both tasks, while only one of the tasks is subtracted. Accordingly, activation observed in this contrast may be related to the respective other (non-subtracted) single task and/or the dual task. Thus, in the contrast DT-VIS, activity may be related to A and/or D, while in the contrast DT-AUD, it may be related to V and/or D. Consequently, this contrast is also not suitable to test for dual-task specific-activations.

It has been argued that this comparison is valid if one aims to show under-additive effects in the dual task. As an example, one might want to show that visual areas show less activity during the dual task as compared to the visual single task and take this as an indication that the requirement to divide attention in the dual task results in reduced stimulus processing. Thus, if DT – VIS results in de-activation, one would infer that activity decreased in the dual task relative to the visual single task. However, this reasoning disregards the fact that the other single task (AUD in the example) may de-activate the identified area. This de-activation may cause the DT condition to show lower activation levels than the VIS condition, although the activity of DT is still just the sum of AUD and VIS. Accordingly, this contrast should also not be used for identifying dual-task-specific areas in cases in which under-additive effects are expected.

Contrast 3: DT – Mean of single tasks

Since subtracting one single task from the dual task is not optimal, we may consider subtracting the mean of both single tasks from the dual task: DT – (VIS + AUD) / 2. Note that this is equivalent to comparisons of two dual-task conditions with both single tasks, e.g. (DT1 + DT2) – (VIS + AUD) or 2DT – (VIS + AUD). However, this approach may underestimate the effects of the single tasks. Let us again take the example of the visual cortex which is activated equivalently in the visual single task and the dual task, but not in the auditory single task. Using this contrast, we would subtract only 50% of the visual cortex activity evoked by VIS, so that in the dual-task condition 50% of the visual cortex activity would remain. Thus, if the activity is strong enough, we may identify visual cortex activation as dual-task-specific although the dual task has the same activation level as the visual single task.

While the above arguments imply that this contrast is not suitable to test for dual-task-specific effects, circumstances are conceivable in which this contrast may actually be suitable. To illustrate this, let us assume a mechanistic cognitive model in which a process or demand, such as a motor response, is either present or absent, ignoring parametric differences in the demands on the process. For this contrast to be valid, we have to assume a cognitive process which is required only once in the dual task and once in each single task. Hypothetical examples include processes such as beginning general task processing at the start of a trial, attending to stimuli in general irrespective of modality, or stopping mind wandering. Since only one instance of such a process is assumed in the dual task, it is correct to subtract only 50% of each single-task activity. Thus, given this assumption, activation in this contrast may indicate true dual-task-specific activation. However, the usual processes assumed to be necessary for task processing, such as stimulus perception, memory retrieval, response selection, and motor execution, are required twice in the dual task, that is, once for each component task. Accordingly, we conclude that this contrast is not suitable to test for dual-task-specific activation unless it can be assumed that the investigated process is required only once in the dual task and once in each single task.

Contrast 4: DT – Sum of single tasks

Since subtracting the mean of the single tasks may underestimate the effects of the single tasks, subtracting the sum of the single tasks from the dual task may be an alternative: DT – (VIS + AUD). This contrast seems promising, because we fully account for both single tasks, so that observed activations cannot be related to single-task processing and consequently must be dual-task-specific. However, the problem of this contrast is that the task-unspecific component u is subtracted twice (once for each single task) from the dual task in which it is present only once (cf. Figure 1). Thus, this contrast underestimates the dual-task-specific effect by the amount of the task-unspecific effect; in other words, it is too conservative and the probability of a type-II error (β error) is increased.

The over-conservativeness of this contrast has advantages and disadvantages. A profound advantage of this contrast is that *if* it reveals an activation, one can be sure that it is dual-task-specific. However, this advantage is countered by four disadvantages owing to the fact that we subtract the task-unspecific component twice rather than only once. First, if we observe an activation, the size, amount, and/or strength of the activation is underestimated. Second, the sensitivity, that is, the likelihood of observing dual-task-specific activation, is reduced – which is critical since dual-task specific effects tend to be small. Third, if no dual-task activations are observed, the result cannot be taken as indicating that there are no dual-task-specific activations (generally, caution is advised if interpreting null-findings). Fourth, because subtracting the task-unspecific component twice shifts the activation into the negative direction, this contrast is too liberal for de-activations (i.e., under-additive effects; cf. Area 9 in Table 2). Thus, de-activations revealed by this contrast should be interpreted with caution due to the increased probability of a type-I error (α error). Accordingly, if we assume a task-unspecific component, the contrast is not optimal, since the unspecific component is subtracted twice instead of once.

However, a recent proposition (e.g. Shulman et al., 2007) questions the assumption of a task-unspecific activity component u, and thus renders this contrast perfectly valid to detect dual-task-specific activation and deactivation. For this, we have to consider what actually happens neurally when a change from the resting state to the state of task processing takes place. Above, we assumed that the brain has some task-unspecific baseline activity, and that task-related activity is on top of this activity (Gusnard & Raichle, 2001). However, it has been argued (e.g. Shulman et al., 2007) that the full activity of an area is devoted to the task; that is, if an area is involved in task processing, the task-unspecific baseline activity contributes fully to task processing. As an example, if an area is 50% active during rest, and the activity increases to 70% during task processing, task processing would be associated with 70% activity – instead of the 20% derived by a subtraction approach (Morcom & Fletcher, 2007). Thus, on the assumption that all activity is task-related (i.e., there is no task-unrelated component u: u = 0), the contrast DT – Sum of the single tasks is optimal (Supplementary Table 3). Recall that all disadvantages of this contrast were related to the fact that the task-unrelated effect u would be subtracted twice, although it is present only once in the dual task. Importantly, if u = 0, all the disadvantages considered above disappear. However, this view is not undisputed (Morcom & Fletcher, 2007) and empirical evidence supporting this view is limited to sensory areas (e.g. Pasley et al., 2007; Uludag et al., 2004). Consequently, it remains to be seen whether a task-unrelated activity component should generally be taken into account or not.

In summary, if this contrast reveals an activation, we can be sure that it is dual-task-specific. However, we should be aware that the activity is probably underestimated. In addition, the results of the contrast cannot be validly interpreted if no activation or a deactivation is found. Thus, while this contrast is in principle suitable for identifying dual-task-specific areas, it is not optimal. However, if we reject the assumption of a task-unrelated activity component, the disadvantages do not apply any longer and this contrast is optimal.

Contrast 5: Interaction contrast (DT – AUD) – (VIS – Baseline)

In order to discuss the rationale of the following interaction contrast, let us consider the dual-task situation as a 2 x 2 factorial design (Figure 2). With respect to our example, the first factor is the visual task, and this factor has the levels "task present" and "task absent". The second factor is the auditory task, again with the levels "task present" and "task absent". This results in four conditions: 1) the dual-task condition (DT), that is, both tasks present; 2) the visual singe-task condition (VIS), that is, visual-task present and auditory task absent; 3) the auditory single-task condition (AUD), that is, auditory task present and visual task absent; and 4) a baseline condition (BASE), that is, both tasks absent.

In this notation, dual-task-specific effects are represented by an interaction of both factors (i.e., tasks). In other words, if one performs, say, the auditory task, what is assessed is whether the neural activity is different depending on whether the visual task had to be performed concurrently or not. Thus, to test for dual-task-specific, that is, over- or under-additive, effects, we can employ the interaction contrast: (DT – AUD) – (VIS – BASE). [Footnote: Note that the notation (DT – AUD) – (VIS – BASE) is equivalent to (DT – VIS) – (AUD – BASE). For the reversed contrast, that is, to test for under-additive effects, the (equivalent) contrasts (AUD – DT) – (BASE – VIS) or (VIS – DT) – (BASE – AUD) can be used.] If this contrast reveals activation, it cannot be related to the component tasks AUD and VIS.

It is interesting to note that this contrast can be reformulated to (DT + BASE) – (AUD + VIS). Thus, as in Contrast 4 (DT – Sum of single tasks), we subtract the sum of the single tasks. However, Contrast 4 under-estimates dual-task-specific activity because the task-unspecific component u is subtracted twice, while it is present only once in the dual-task. In the present interaction contrast, the BASE condition, which is an estimator of the task-unspecific activity component u, is added to the dual-task activity D, so that it is correct to subtract the task-unspecific activity component u twice (cf. Figure 1). Consequently, the interaction contrast is not over-conservative and it does not suffer from the disadvantages associated with Contrast 4.

However, while this contrast is optimal in theory, it is potentially problematic from a pragmatic point of view. In the interaction contrast, the resting baseline is added to the dual-task condition and then compared to the sum of the single-task conditions. Accordingly, this approach depends on the assumption that the resting baseline is a good estimator of the task-unrelated component u, that is, the resting or base state of the brain. However, a problematic finding for that assumption is the observation that certain cognitive processes associated with mentalizing, such as thinking, thoughts, and/or inner speech, may occur during prolonged resting states (Gusnard & Raichle, 2001; Mazoyer et al., 2001). Such additional processes may represent a severe confound because in the interaction contrast, dual-task and resting baseline effects are combined and merged, so that it cannot be decided whether an activation is caused by the dual task or by the resting baseline condition. To illustrate this, let us assume that participants do not follow the instruction to stay mentally at rest during the baseline, but instead perform some mental activity such as remembering their last vacation. Thus, activity during BASE may not only consist of the task-unspecific component u, but also of an additional activity component (denoted "M"). In our example, M may be related to memory retrieval. Thus, for Area-MAVD, an activation revealed by the interaction contrast is due to components M and/or D ((DT + BASE) – (AUD+VIS) = (uAVDuM) – (uAuV) = DM), rather than D alone, as it would be required for an optimal contrast. To avoid such a confound, one could use a baseline condition which is less prone to mentalizing processes. An example would be to use null-events in an event-related design, in which the trial onsets are unpredictable, for instance, as a result of temporal jittering (Burock et al., 1998; Friston et al., 1999; Josephs & Henson, 1999). Due to the short duration and unpredictable appearance of null-events, participants might be much more likely to stay focused on the task, rather than starting to mind-wander.

We conclude that the interaction contrast is theoretically the best choice to identify dual-task-specific areas. However, it requires the assumption that the employed baseline condition is a valid estimate of the task-unrelated component u.

Contrast 6: Conjunction (DT – AUD) ∩ (DT – VIS)

As outlined above, the interaction contrast has the disadvantage that it includes the resting baseline. To circumvent this problem, one could use a conjunction contrast which does not involve the resting baseline. In order to conduct a conjunction analysis, first the two independent contrasts DT – AUD and DT – VIS are calculated. In the second step, only areas are considered that are active in both contrasts, since such areas are related to the dual-task-specific component D. This is because the contrast DT – AUD may reveal only activity components D and V, while the contrast DT – VIS may reveal only components D and A. Following set theory and the logical "AND", the result of the contrast (DT – AUD) ∩ (DT – VIS) in terms of activity components is (D, V) ∩ (D, A), which is D. Thus, an area activated in both contrasts must be related to the dual-task-specific component D.

However, the interpretation of activations revealed by the conjunction analysis as dual-task-specific is feasible only if there is no single-task-related activation in the activated area. To illustrate this, consider for instance Area-AV which shows significant activation in both single tasks which combines additively in the dual task. In this area, the contrast DT – AUD will reveal significant activation which is caused by the VIS condition. Similarly, the contrast DT – VIS will reveal significant activation which is caused by the AUD condition. Thus, the conjunction analysis would identify Area-AV as dual-task-specific although it just shows the sum of the component tasks.

In order to avoid such false-positive results, it is important to ensure that *both* single tasks should have *no* activation at all (and not only no significant activation), since significant activations can arise if there are sub-threshold single- and dual-task effects (Area 11 in Table 2). To illustrate this, suppose that there is a brain area with the following activation profile: Let us assume the level of activity in each single task is only 75% of what would be required for this area to be significantly activated. In addition, there is a dual-task-specific effect, but again only with 75% of the activity level required for reaching significance. When compared to BASE, we would observe a significant activation in the dual-task condition in such an area, since the activities of the single tasks and the dual task add up (3 x 75% = 225%, 100% is threshold for statistical significance), while the activation in the single tasks is sub-threshold. Crucially, although there is no significant dual-task-specific effect, the conjunction analysis would indicate one. This is because both component comparisons DT – AUD (225% - 75% = 150%) and DT – VIS (225% - 75% = 150%) would be significant. To summarize, if there is single-task-related activity in the area identified as dual-task-specific by the conjunction analysis, subthreshold effects of the dual task and the single tasks may have added up to yield a false-positive significant result.

Finally, it should be noted that it is only partially true that no resting baseline is required. While a resting baseline is indeed not involved in the conjunction analysis directly, it is required for testing whether the dual-task-specific areas show activation in the single-task conditions. Since these contrasts (AUD – BASE and VIS – BASE) are an important prerequisite, the conjunction approach is indirectly affected by the same criticism of using a resting baseline as we have described for the interaction contrast (Contrast 5) above.

Taken together, the conjunction analysis is a valid approach to test for dual-task-specific effects. However, it presupposes that there is no, not even sub-threshold, activation during the single tasks in the areas of interest.

Which contrast to use?

Taken together, our evaluation showed that there is no perfect contrast for the identification of dual-task-specific brain areas if an approach is followed that compares the dual-task with some sort of single-task activity. Nevertheless, the contrasts can be divided into two groups: contrasts in principle suitable for identifying dual-task-specific effects (Contrasts 4-6), and contrast not suitable for this purpose (Contrasts 1-3).

If over-additive effects (i.e., the dual task showing more/higher activation) are of interest, then Contrast 4 (DT – sum of single tasks) is probably the best one to start with. However, one should be aware that effect sizes may be underestimated and that de-activation (i.e., under-additive effects) and absence of activation cannot be validly interpreted.

Contrast 5 (interaction contrast [(DT-AUD)-(VIS-BASE)]) is the second best choice to test for dual-task-specific effects. However, a limitation of this contrast arises from the practical problem of finding a condition which is a good estimator for the task-unspecific effect u. If we assume that, for example, a resting baseline is a good estimator, the interaction contrast provides an exact estimate of over- and under-additive dual-task-specific effects. Thus, this contrast is advisable if Contrast 4 reveals no activation, if deactivations are of interest, or if a more exact estimate of the effect size is desired.

Contrast 6 (conjunction analysis) is the third best choice because it relies on the potentially hard-to-fulfill assumption that the single tasks must not activate the dual-task related areas. This restricts this contrast to the identification of areas newly activated by the dual task, while it is not capable of detecting over-/under-additive modulations of areas already involved in single-task performance. Moreover, the resting baseline is also involved in this contrast, albeit only indirectly. Therefore, we suggest to use contrasts 4 and 5 before resorting to this contrast.

Contrasts 1-3 are not suitable to test for dual-task-specific effects and should therefore only be used to identify dual-task related areas in the context of a general research question.

Which single tasks to use?

In behavioral dual-task research, it has sometimes been suggested to use a single-task condition which resembles the dual-task condition as closely as possible (Pashler, 1994). For instance, one might present both stimuli, the visual and the auditory one, in the single-task conditions as well, although participants have to respond to one stimulus only. Without engaging in a detailed discussion about dissecting individual cognitive demands in dual-task processing, it is worth considering the effects of such a single-task condition on the above-described contrasts. With respect to the contrasts considered suitable for identifying dual-task-specific activations, it seems problematic to present both stimuli also in the single-task conditions. The reason is that then too much stimulus-related processing is subtracted from the dual task. This is evident for instance in Contrast 4 (DT – Sum of single tasks). In the dual task, one visual and one auditory stimulus are presented. If the single tasks always incorporate both stimuli, we would subtract the activity of two auditory and two visual stimuli instead of one, which is incorrect. Therefore, unless there are specific reasons why both stimuli should be presented in the single tasks, we recommend designing the single tasks as closely as possible to the component tasks of the dual task.

Previous dual-task research

Contrasts which may not be optimal for the identification of dual-task specific effects have been used previously. However, it is important to keep in mind that the results derived by these contrasts are perfectly valid from a statistical point of view (as opposed, for instance, to the criticisms recently raised by (Vul et al., 2009)) and Kriegeskorte et al. (2009) regarding "non-independent" analyses). If at all, the *interpretation* of the results may be beyond what is warranted by the data. [Footnote: Since an evaluation of previous studies regarding whether the interpretation is beyond what the data allow for seems too subjective, we refrain from such an analysis.]

The assumption of a task-unspecific activity component

As outlined above (Contrast 4: DT – sum of single tasks), one may argue that it is not justified to assume that each activation can be decomposed into a task-specific component and a task-unspecific baseline component (denoted "u" in Table 1, and set to 1 in Table 2). Following this argument and assuming that there is no task-unspecific component (u = 0), Table 1 is easily adjusted by subtracting "u" from each cell in Table 1 part (A). By recalculating the contrasts, it becomes evident that the performance of the contrasts does not change, except for Contrast 4 (DT – sum of single tasks) which now performs perfectly (see Supplementary Table 3 as well). Thus, following this argument, Contrast 4 would remain the best contrast, while the criticism of all other contrasts would still be valid.

Other approaches to investigating dual tasks

The present considerations showed that each contrast has some disadvantages. Accordingly, the question arises whether there would be other approaches to investigate the functional neuroanatomical correlates of dual-task performance.

One other approach would be *parametric manipulation*. In this approach, the demands on a process which is assumed to be involved in dual-task performance are parametrically manipulated and the effects of this manipulation on the neural substrate are assessed. For instance, previous studies manipulated the demands on the response selection difficulty (Stelzel et al., 2006), the demands on working memory (Stelzel et al., 2008), the level of practice (Dux et al., 2009; Erickson et al., 2007), and the demands involved in controlling the order in which the tasks are processed (Szameitat et al., 2006). The advantage of parametric manipulations is that the investigated process can easily be identified by a direct comparison of the two (or more) conditions used for parametric manipulation. For instance, to identify the functional neuroanatomical correlates of the response selection (RS) process in dual-task performance, a task with a difficult RS (e.g., 4 alternative stimulus-response mappings) may be compared to a task with an easy RS (e.g., 2 stimulus-response mappings). The corresponding contrast would be RS(difficult) – RS(easy). However, while parametric manipulations are perfectly suited to identify *a-priori* hypothesized processes, they are usually unable to identify the whole set of dual-task-specific areas. In our example, we would have identified the area associated with RS, but we would not have been able to show other dual-task-specific effects, for instance related to stimulus perception or motor execution.

However, recently it has been proposed that dual-task specific effects can be identified by a parametric manipulation as well. For this, the temporal overlap (stimulus onset asynchrony, SOA) between both tasks has to be manipulated (Dux et al., 2006; Jiang et al., 2004). For instance, in the study of Jiang et al. (2004), they implemented dual-task blocks in which a dual-task trial was presented every 3s. In the dual task, the stimuli were presented simultaneously, that is, SOA = 0 ms. In addition, they had single-task blocks in which the single tasks were presented alternatingly every 1.5 s. In other words, they temporally stretched the component tasks apart, while the conditions were equal with regard to all other aspects (however, the conditions might also differ in how much they are affected by nonlinear effects due to hemodynamic refractoriness, see next section for a detailed discussion). The logic is that potential dual-task-specific processes, such as coordination of two concurrent tasks, should be required only in the short-SOA (SOA = 0) condition, so that the contrast to identify dual-task specific areas would be DT(SOA 0ms) – DT(SOA 1500ms). However, while this approach seems very reasonable, caution is advisable as previous studies (Stelzel et al., 2009; Szameitat, 2003) have shown that the activation does indeed decrease if the temporal overlap is decreased (i.e., the SOA is increased), but only within a limited range of a couple of hundred milliseconds. If the SOA becomes longer (e.g., > 800 ms), activation in some dual-task-specific areas increases again. Whether this pattern is due to additional qualitative processing differences between SOAs beyond the quantitative differences intended to be induced by parametric manipulation of the SOA, is presently unknown. However, as long as this finding is not fully understood, studies assuming a monotonic relationship between SOA and activation of dual-task-specific brain areas may result in misguided conclusions.

Taken together, parametric manipulation approaches have the advantage that the analysis is straightforward, but the disadvantage that usually only specific, *a-priori* hypothesized processes can be investigated.

Nonlinearities

The above discussion of the contrasts assumes linearity of the measured signal. In particular, it is assumed that the measured signal of two simultaneous events is identical to the measured signal of the events when presented in isolation (assumption of superposition). For fMRI, it has been shown that superposition holds only if the events are separated by at least 2-3 seconds (e.g. Boynton et al., 1996). This is clearly not the case in dual-task performance where the two events, i.e. the two tasks, are typically presented within less than 1.5s. [Footnote: By ensuring a sufficient inter-trial-interval nonlinear effects due to rapid trial presentation can be avoided and will not be discussed here.] Thus, due to the properties of the BOLD response, nonlinear effects are likely to be present in fMRI dual-task studies. But what are the consequences of such nonlinear effects?

First, we have to consider which areas are affected by nonlinear effects at all. These are those areas which respond to more than one task component, i.e. Area-AV and Area-AVD (plus Area-AD and -VD as given in Table 2). However, an area exclusively responsive to only one task should not be affected by such nonlinearities. In the present context, this holds in particular for Area-D, i.e. areas newly activated by the dual-task which are not active during single-task performance should not be affected by nonlinearities.

Second, it has been shown that the hemodynamic response to successive presentations of the same stimulus is slightly delayed and, most importantly, slightly decreased in amplitude (hemodynamic refractoriness). Thus, we would expect the dual-task specific areas Area-AVD, -AD, and -VD to be less activated than predicted by the sum of the components A, V, and D. In other words, nonlinear effects work against the detection of over-additive dual-task specific activation. Consequently, if over-additive dual-task specific activations are shown, they are valid. However, the effect size (e.g. extent and amplitude of activation) is potentially reduced. Opposed to this, if under-additive effects are shown, they could be caused either by a genuine under-additivity due to dual-task performance or by a reduction in signal-strength due to nonlinear effects. Along the same lines, if no over-additive activation is observed in the dual-task, this finding cannot be interpreted. Taken together, if dual-task activations are shown, they may be underestimated due to possible nonlinear effects but will be valid.

Finally, the question arises whether such nonlinearities could be corrected. While a number of approaches dealing with nonlinearities have been put forward (e.g. Deneux & Faugeras, 2006; Friston et al., 1998; Friston et al., 2000), their application to dual-task performance may be problematic. One reason is that to estimate the size of the nonlinear effect an SOA manipulation seems most appropriate. However, in such a study the size of nonlinear and dual-task specific effects may be highly correlated. The shorter the SOA, the stronger the attenuation of the fMRI signal due to nonlinear (refractory) effects. Opposed to this, typically it is assumed that demands on cognitive processes, and consequently neural processing and fMRI signal strength, in dual-task performance increase with shorter SOA.[Footnote: Accordingly, activation increase due to increased cognitive demands and activation decrease due to stronger hemodynamic refractoriness may (at least theoretically) cancel each other out. This should be kept in mind for studies aimed at identifying dual-task specific areas by an SOA manipulation, in particular if these studies show a null finding (Jiang et al., 2004)).] For instance, if nonlinearities are modeled using Volterra series (Friston et al., 1998), an additional regressor modeling the size of the nonlinear effect (typically depending on the amount of temporal overlap) may be included in the statistical model. However, such an additional regressor would be perfectly correlated with a potential SOA manipulation, and therefore with the amount of proposed cognitive demands. Thus, presently it seems unclear whether hemodynamic nonlinear effects can be disentangled from cognitive effects in a study only varying the SOA.

One conceivable approach to disentangle nonlinear and cognitive effects is to use an SOA manipulation in combination with some other parametric manipulation of a dual-task specific process. For instance, Dux et al. (2006) manipulated the SOA and analyzed fast and slow task 1 response times separately (which is equivalent to a parametric manipulation). They localized dual-task specific areas associated with the response selection by showing an interaction between response time and SOA which cannot be explained by nonlinear effects. However, as already mentioned above, in parametric manipulation approaches only *a priori* defined cognitive processes can be investigated, while a general identification of a dual-task network is not possible.

Taken together, nonlinearities may reduce the effect size of dual-task specific activations. As a consequence, observed dual-task specific activations, though valid, may be underestimated, and absence of dual-task specific effect or under-additive effects must be interpreted with caution.

Related research areas

While the current manuscript focuses on dual-task paradigms, the same arguments hold for any study in which the combined effects of two processes, two demands, two cognitive mechanisms, *et cetera* on the resulting neural activity are investigated (cf. Figure 2). Examples are investigations of divided attention, multisensory integration, bimanual movements, effects of conversation on driving performance, and so forth, which aim at assessing the neural effects engendered by the combined processing of two information sources. For instance, in a study of multisensory integration, one may present either a spoken word, a video-clip of a person speaking the word, or both stimuli at the same time. If one is interested in assessing what is specific to the multisensory integration, that is, which cannot be accounted for by the individual presentation of mono-sensory stimulation, the arguments outlined above apply in the same way. Another example is divided attention. Here, one may ask participants to respond to a specific target word presented auditorily. Separate streams of spoken words may be presented either to the left ear, the right ear, or both ears (divided attention condition). Again, if one is interested in what is specific to divided attention, the arguments outlined above apply.

Conclusion

We have shown that in dual-task brain imaging research, it is important to clearly state the research question regarding the level of specificity of dual-task-related activations. In general, the neuroanatomical correlates of dual-task performance can be identified by a variety of methodological approaches and comparisons. For the particular approach of comparing the activity in a dual-task situation with the activity in the two component single tasks, we have argued that some contrasts, such as comparing the dual task with the mean of the single tasks, are interpretable only in a limited way. We suggest using contrasts that can attribute activations as “dual-task-specific”, that is, as activations which are not the result of any effects attributable to the single-task effects. The “safest bet” for this is the potentially over-conservative comparison of the dual task with the sum of the single tasks, which may be complemented by an interaction contrast or a conjunction analysis.

Acknowledgements
TS was supported by Cotesys (project no. 439).

Figures & Tables

Figure 1. Activity components for the different tasks. Activity in the baseline condition (BASE) is assumed to reflect only the task-unspecific effect (u). Activity in the auditory (visual) task AUD (VIS) is composed of the task-unspecific effect u plus the auditory (visual) task specific effect. Activity in the dual task is composed of the task-unspecific effect u, the sum of the task specific effects of the component tasks AUD and VIS, plus a dual-task specific effect D.

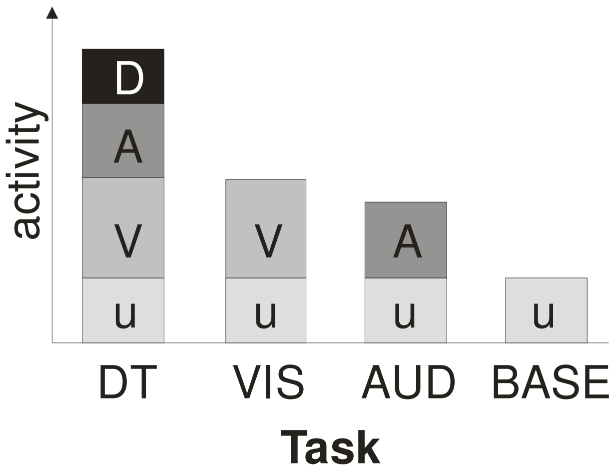

Figure 2. The dual-task situation expressed as a factorial design. Each single task constitutes a factor with two levels ("task present" and "task absent"). An example for the dual-task situation is embedded in the figure. For multisensory integration paradigms, the bi-sensory stimulation is equivalent to DT and each separate mono-sensory stimulation to the single tasks. For divided attention paradigms, the divided attention condition is equivalent to DT, and the focused attention on each separate sub-component to the single tasks.

		Single task 1 (VIS)	
		present	*absent*
Single task 2 (AUD)	*present*	Dual task (DT)	Single task 2 (AUD)
	absent	Single task 1 (VIS)	Baseline (BASE)

Table 1.

Performance of the different contrasts for six areas characterized by different hypothetical activation profiles. **(A)** expected activity components for each area and task. Activity associated with unspecific task-component (u), the visual single task (V), the auditory single task (A), the dual-task specific effect (D), and with undesired activity during the baseline (M). For instance, activity in Area-V during the DT condition is expected to consist of u and V. **(B)** results of the different contrasts. Results are marked as correct (bold) or incorrect (italics in brackets) for a contrast suitable to identify dual-task specific activations. Letters denote the potential sources of activation revealed by the contrast. For instance, activation in the contrast 2: DT – VIS in Area-AVD is caused by the auditory component task (A) as well as the dual task (D). no = no activation observed; yes = activation observed.

	Hypothetical area					
	1. Area-V	2. Area-A	3. Area-AV	4. Area-AVD	5. Area-MAVD	6. Area-D
(A) activity components						
BASE	u	u	u	u	uM	u
AUD	u	uA	uA	uA	uA	u
VIS	uV	u	uV	uV	uV	u
DT	uV	uA	uAV	uAVD	uAVD	uD
(B) contrast results						
1: DT-BASE	*(V)*	*(A)*	*(A,V)*	*(A,V,D)*	*(A,V,D,-M)*	**D**
2: DT-AUD	*(V)*	**no**	*(V)*	*(V,D)*	*(V,D,-M)*	**D**
2: DT-VIS	**no**	*(A)*	*(A)*	*(A,D)*	*(A,D,-M)*	**D**
3: DT-Mean of ST	*(0.5V)*	*(0.5A)*	*(0.5A, 0.5V)*	*(0.5A, 0.5V,D)*	*(0.5A, 0.5V,D,-M)*	**D**
4: DT-Sum of ST	*(-u)*	*(-u)*	*(-u)*	*(D,-u)*	*(D,-u)*	*(D,-u)*
5: Interaction	**no**	**no**	**no**	**D**	*(D,M)*	**D**
6: Conjunction	**no**	**no**	*(yes)*	**yes**	no/yes[1]	**yes**

Notes. [1] The result of the conjunction depends on the strength of the activity M. If A and V are significantly larger than M, the conjunction will correctly identify dual-task specific areas, while it won't if A and/or V are not significantly larger than M.

Table 2. Comparable to Table 1, except that numerical calculations and 6 further hypothetical areas are used. Numbers represent hypothetical β-values with the assumption that $\beta > 3.5$ is significantly different from zero, while $\beta < 3.5$ is not. **(A)** Size of task-unspecific component u (arbitrarily set to 1) and of task specific components for auditory task (A), visual task (V) and dual-task specific effect (D) (arbitrarily set to 0 if not activated, to 4 if significantly activated (-4 if deactivated), and to 2 if partially activated). **(B)** Expected total effect size for each task as derived by summation of the relevant activity components given in table part (A). **(C)** reflects the outcome for the contrasts as calculated based on the hypothetical β-values in (B). Results are marked as correct (bold face) or incorrect (italics in brackets) for a contrast suitable to identify dual-task specific activations. Numbers reflect the resulting β-values, except for contrast 6 (Conjunction) for which 1 indicates significant dual-task related activation, and 0 no significant activation.

Abbreviations: VIS = visual single task, AUD = auditory single task, DT = dual task, BASE = baseline, ST = single tasks. Interaction contrast = [(DT – AUD) – (VIS – BASE)]. Conjunction = [(DT – AUD) ∩ (DT – VIS)]. subthresh = activation above zero but below threshold for significance.

	Hypothetical area											
	1: only VIS (V)	2: only AUD (A)	3: AUD, AUD (AV)	4: AUD, VIS, DT (AVD)	5: Mentalizing, AUD, VIS, DT (MAVD)	6: only DT (D)	7: AUD, DT	8: VIS, DT	9: VIS, AUD, DT (underadditive)	10: VIS, AUD, DT (DT subthresh.)	11: VIS, AUD, DT (all subthresh.)	12: no activation
(A) size of activity component												
u	1	1	1	1	1	1	1	1	1	1	1	1
M	0	0	0	0	4	0	0	0	0	0	0	0
A	0	4	4	4	4	0	4	0	4	4	2	0
V	4	0	4	4	4	0	0	4	4	4	2	0
D	0	0	0	4	4	4	4	4	-4	2	2	0
(B) size of task effect												
BASE (u+M)	1	1	1	1	5	1	1	1	1	1	1	1
AUD (u+A)	1	5	5	5	5	1	5	1	5	5	3	1
VIS (u+V)	5	1	5	5	5	1	1	5	5	5	3	1
DT (u+V+A+D)	5	5	9	13	13	5	9	9	5	11	7	1
(C) contrast results												
1: DT-BASE	*(4)*	*(4)*	*(8)*	*(12)*	*(8)*	**4**	*(8)*	*(8)*	*(4)*	*(10)*	*(6)*	**0**
2: DT-AUD	*(4)*	**0**	*(4)*	*(8)*	*(8)*	**4**	**4**	*(8)*	*(0)*	*(6)*	*(4)*	**0**
2: DT-VIS	**0**	*(4)*	*(4)*	*(8)*	*(8)*	**4**	*(8)*	**4**	*(0)*	*(6)*	*(4)*	**0**
3: DT-Mean of ST	*(2)*	*(2)*	*(4)*	*(8)*	*(8)*	**4**	*(6)*	*(6)*	*(0)*	*(6)*	*(4)*	**0**
4: DT-Sum of ST	*(-1)*	*(-1)*	*(-1)*	*(3)*	*(3)*	*(3)*	*(3)*	*(3)*	*(-5)*	*(1)*	*(1)*	*(-1)*
5: Interaction	**0**	**0**	**0**	**4**	*(8)*	**4**	**4**	**4**	**-4**	**2**	**2**	**0**
6: Conjunction	**0**	**0**	*(1)*	**1**	?[(1)]	**1**	**1**	**1**	*(0)*	*(1)*	*(1)*	**0**

Notes. [(1)] see Table 1.

Supplementary Online Material

Supplementary Table 3. Similar to Table 2, with the exception that no task-unspecific effect is assumed, i.e. u = 0. Results of the contrasts are identical to Table 2 with the exception of Contrast 4 (DT – sum of single tasks) which now performs perfect. For further details, see Table 2.

	Hypothetical area											
	1: only VIS (V)	2: only AUD (A)	3: AUD, AUD (AV)	4: AUD, VIS, DT (AVD)	5: Mentalizing, AUD, VIS, DT (MAVD)	6: only DT (D)	7: AUD, DT	8: VIS, DT	9: VIS, AUD, DT (underadditive)	10: VIS, AUD, DT (DT subthresh.)	11: VIS, AUD, DT (all subthresh.)	12: no activation
(A) size of activity component												
u	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	4	0	0	0	0	0	0	0
A	0	4	4	4	4	0	4	0	4	4	2	0
V	4	0	4	4	4	0	0	4	4	4	2	0
D	0	0	0	4	4	4	4	4	-4	2	2	0
(B) size of task effect												
BASE (u+M)	0	0	0	0	4	0	0	0	0	0	0	0
AUD (u+A)	0	4	4	4	4	0	4	0	4	4	2	0
VIS (u+V)	4	0	4	4	4	0	0	4	4	4	2	0
DT (u+V+A+D)	4	4	8	12	12	4	8	8	4	10	6	0
(C) contrast results												
1: DT-BASE	*(4)*	*(4)*	*(8)*	*(12)*	*(8)*	**4**	*(8)*	*(8)*	*(4)*	*(10)*	*(6)*	**0**
2: DT-AUD	*(4)*	**0**	*(4)*	*(8)*	*(8)*	**4**	**4**	*(8)*	*(0)*	*(6)*	*(4)*	**0**
2: DT-VIS	**0**	*(4)*	*(4)*	*(8)*	*(8)*	**4**	*(8)*	**4**	*(0)*	*(6)*	*(4)*	**0**
3: DT-mean of ST	*(2)*	*(2)*	*(4)*	*(8)*	*(8)*	**4**	*(6)*	*(6)*	*(0)*	*(6)*	*(4)*	**0**
4: DT-sum of ST	**0**	**0**	**0**	**4**	**4**	**4**	**4**	**4**	**-4**	**2**	**2**	**0**
5: Interaction	**0**	**0**	**0**	**4**	*(8)*	**4**	**4**	**4**	**-4**	**2**	**2**	**0**
6: Conjunction	**0**	**0**	*(1)*	**1**	?(1)	**1**	**1**	**1**	*(0)*	*(1)*	*(1)*	**0**

Notes. (1) The result of the conjunction depends on the strength of the activity M. If A and V are significantly larger than M, the conjunction will correctly identify dual-task specific areas, while it won't if A and/or V are not significantly larger than M.

References

Adcock, R. A., Constable, R. T., Gore, J. C., & Goldman-Rakic, P. S. (2000). Functional neuroanatomy of executive processes involved in dual-task performance. *Proceedings of the National Academy of Sciences of the United States of America, 97*(7), 3567-3572.

Baddeley, A. D. (1990). *Human Memory: Theory and practice*. Hove (UK): Lawrence Erlbaum Associates.

Boynton, G. M., Engel, S. A., Glover, G. H., & Heeger, D. J. (1996). Linear systems analysis of functional magnetic resonance imaging in human V1. *J Neurosci, 16*(13), 4207-4221.

Bunge, S. A., Klingberg, T., Jacobsen, R. B., & Gabrieli, J. D. (2000). A resource model of the neural basis of executive working memory. *Proceedings of the National Academy of Sciences of the United States of America, 97*(7), 3573-3578.

Burock, M. A., Buckner, R. L., Woldorff, M. G., Rosen, B. R., & Dale, A. M. (1998). Randomized event-related experimental designs allow for extremely rapid presentation rates using functional MRI. *Neuroreport, 9*(16), 3735-3739.

Deneux, T., & Faugeras, O. (2006). Using nonlinear models in fMRI data analysis: model selection and activation detection. *Neuroimage, 32*(4), 1669-1689.

D'Esposito, M., Detre, J. A., Alsop, D. C., Shin, R. K., Atlas, S., & Grossman, M. (1995). The neural basis of the central executive system of working memory. *Nature, 378*(6554), 279-281.

Duncan, J. (1979). Divided attention: The whole is more than the sum of its parts. Dual-task interference as an indicator of on-line programming in simple movement sequences. *Journal of Experimental Psychology: Human Perception & Performance, 5*(2), 216-228.

Dux, P. E., Ivanoff, J., Asplund, C. L., & Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved FMRI. *Neuron, 52*(6), 1109-1120.

Dux, P. E., Tombu, M. N., Harrison, S., Rogers, B. P., Tong, F., & Marois, R. (2009). Training improves multitasking performance by increasing the speed of information processing in human prefrontal cortex. *Neuron, 63*(1), 127-138.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., et al. (2007). Training-induced functional activation changes in dual-task processing: an FMRI study. *Cereb Cortex, 17*(1), 192-204.

Erickson, K. I., Colcombe, S. J., Wadhwa, R., Bherer, L., Peterson, M. S., Scalf, P. E., et al. (2005). Neural correlates of dual-task performance after minimizing task-preparation. *Neuroimage, 28*(4), 967-979.

Friston, K. J., Josephs, O., Rees, G., & Turner, R. (1998). Nonlinear event-related responses in fMRI. *Magn Reson Med, 39*(1), 41-52.

Friston, K. J., Mechelli, A., Turner, R., & Price, C. J. (2000). Nonlinear responses in fMRI: The Balloon model, Volterra kernels, and other hemodynamics. *NeuroImage, 12*(4), 466-477.

Friston, K. J., Zarahn, E., Josephs, O., Henson, R. N., & Dale, A. M. (1999). Stochastic designs in event-related fMRI. *NeuroImage, 10*(5), 607-619.

Goldberg, T. E., Berman, K. F., Fleming, K., Ostrem, J., Horn, J. D. V., Esposito, G., et al. (1998). Uncoupling Cognitive Workload and Prefrontal Cortical Physiology: A PET rCBF Study. *NeuroImage, 7*(4), 296-303.

Gusnard, D. A., & Raichle, M. E. (2001). Searching for a baseline: Functional imaging and the resting human brain. *Nature Reviews Neuroscience, 2*(10), 685-694.

Herath, P., Klingberg, T., Young, J., Amunts, K., & Roland, P. (2001). Neural correlates of dual task interference can be dissociated from those of divided attention: An fMRI study. *Cerebral Cortex, 11*(9), 796-805.

Hsieh, L., Young, R. A., Bowyer, S. M., Moran, J. E., Genik, R. J., 2nd, Green, C. C., et al. (2009). Conversation effects on neural mechanisms underlying reaction time to visual events while viewing a driving scene: fMRI analysis and asynchrony model. *Brain Res, 1251*, 162-175.

Jaeggi, S. M., Seewer, R., Nirkko, A. C., Eckstein, D., Schroth, G., Groner, R., et al. (2003). Does excessive memory load attenuate activation in the prefrontal cortex? Load-dependent processing in single and dual tasks: functional magnetic resonance imaging study. *Neuroimage, 19*(2 Pt 1), 210-225.

Jiang, Y. (2004). Resolving dual-task interference: an fMRI study. *Neuroimage, 22*(2), 748-754.

Jiang, Y., Saxe, R., & Kanwisher, N. (2004). Functional magnetic resonance imaging provides new constraints on theories of the psychological refractory period. *Psychol Sci, 15*(6), 390-396.

Josephs, O., & Henson, R. N. (1999). Event-related functional magnetic resonance imaging: Modelling, inference and optimization. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 354*(1387), 1215-1228.

Just, M. A., Carpenter, P. A., Keller, T. A., Emery, L., Zajac, H., & Thulborn, K. R. (2001). Interdependence of nonoverlapping cortical systems in dual cognitive tasks. *NeuroImage, 14*(2), 417-426.

Just, M. A., Keller, T. A., & Cynkar, J. (2008). A decrease in brain activation associated with driving when listening to someone speak. *Brain Res, 1205*, 70-80.

Klingberg, T. (1998). Concurrent performance of two working memory tasks: Potential mechanisms of interference. *Cerebral Cortex, 8*(7), 593-601.

Klingberg, T., & Roland, P. E. (1997). Interference between two concurrent tasks is associated with activation of overlapping fields in the cortex. *Brain Research. Cognitive Brain Research, 6*(1), 1-8.

Koechlin, E., Basso, G., Pietrini, P., Panzer, S., & Grafman, J. (1999). The role of the anterior prefrontal cortex in human cognition. *Nature, 399*(6732), 148-151.

Kriegeskorte, N., Simmons, W. K., Bellgowan, P. S., & Baker, C. I. (2009). Circular analysis in systems neuroscience: the dangers of double dipping. *Nat Neurosci, 12*(5), 535-540.

Marois, R., & Ivanoff, J. (2005). Capacity limits of information processing in the brain. *Trends Cogn Sci, 9*(6), 296-305.

Mazoyer, B., Zago, L., Mellet, E., Bricogne, S., Etard, O., Houde, O., et al. (2001). Cortical networks for working memory and executive functions sustain the conscious resting state in man. *Brain Res Bull, 54*(3), 287-298.

Morcom, A. M., & Fletcher, P. C. (2007). Does the brain have a baseline? Why we should be resisting a rest. *Neuroimage, 37*(4), 1073-1082.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*(2), 220-244.

Pasley, B. N., Inglis, B. A., & Freeman, R. D. (2007). Analysis of oxygen metabolism implies a neural origin for the negative BOLD response in human visual cortex. *Neuroimage, 36*(2), 269-276.

Schubert, T. (2008). The central attentional limitation and executive control. *Front Biosci, 13*, 3569-3580.

Schubert, T., & Szameitat, A. J. (2003). Functional neuroanatomy of interference in overlapping dual tasks: an fMRI study. *Brain Res Cogn Brain Res, 17*(3), 733-746.

Shulman, R. G., Rothman, D. L., & Hyder, F. (2007). A BOLD search for baseline. *Neuroimage, 36*(2), 277-281.

Sigman, M., & Dehaene, S. (2008). Brain mechanisms of serial and parallel processing during dual-task performance. *J Neurosci, 28*(30), 7585-7598.

Smith, E. E., Geva, A., Jonides, J., Miller, A., Reuter-Lorenz, P., & Koeppe, R. A. (2001). The neural basis of task-switching in working memory: Effects of performance and aging. *Proceedings of the National Academy of Sciences of the United States of America, 98*(4), 2095-2100.

Stelzel, C., Brandt, S. A., & Schubert, T. (2009). Neural mechanisms of concurrent stimulus processing in dual tasks. *Neuroimage, 48*(1), 237-248.

Stelzel, C., Kraft, A., Brandt, S. A., & Schubert, T. (2008). Dissociable neural effects of task order control and task set maintenance during dual-task processing. *J Cogn Neurosci, 20*(4), 613-628.

Stelzel, C., Schumacher, E. H., Schubert, T., & D'Esposito, M. (2006). The neural effect of stimulus-response modality compatibility on dual-task performance: an fMRI study. *Psychol Res, 70*(6), 514-525.

Szameitat, A. J. (2003). *Die Funktionalität des lateral-präfrontalen Cortex für die Verarbeitung von Doppelaufgaben [German]*. Leipzig: Max Planck Institute of Cognitive Neuroscience.

Szameitat, A. J., Lepsien, J., Cramon, D. Y., Sterr, A., & Schubert, T. (2006). Task-order coordination in dual-task performance and the lateral prefrontal cortex: an event-related fMRI study. *Psychol Res, 70*(6), 541-552.

Szameitat, A. J., Schubert, T., Müller, K., & von Cramon, D. Y. (2002). Localization of executive functions in dual-task performance with fMRI. *J Cogn Neurosci, 14*(8), 1184-1199.

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology, 14*, 1-36.

Uludag, K., Dubowitz, D. J., Yoder, E. J., Restom, K., Liu, T. T., & Buxton, R. B. (2004). Coupling of cerebral blood flow and oxygen consumption during physiological activation and deactivation measured with fMRI. *Neuroimage, 23*(1), 148-155.

Vul, E., C., H., Winkielman, P., & Pashler, H. (2009). Puzzlingly high correlations in fMRI studies of emotion, personality, and social cognition. *Perspectives on Psychological Science, 4*, 274-290.

Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance - A review and a theory. *British Journal of Psychology, 43*, 2-19.