Multiple demands on cognitive control in dual-task processing

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Zusammenfassung

Wir führen häufig zwei Aufgaben zeitüberlappend aus, obwohl dadurch in der Regel die Leistung in den individuellen Aufgaben beeinträchtigt wird. In der kognitiven Psychologie wurden Leistungseinbußen in Doppelaufgaben ausgiebig untersucht, um Einblicke in die kognitive Architektur und die Mechanismen der Informationsverarbeitung zu erhalten.

Die Ergebnisse haben eine jahrzehntelange theoretische Kontroverse über die Rolle der kognitiven Kontrolle in Doppelaufgaben entfacht. Kognitive Kontrolle ermöglicht es uns, flexibel und kontextabhängig komplexe Aufgabenanforderungen zu meistern und somit zielgerichtet zu handeln. In Doppelaufgaben könnte kognitive Kontrolle u.a. erforderlich sein, um die Verarbeitung einer Aufgabe gegen interferierende Einflüsse, die aus der zeitlich überlappenden Verarbeitung einer anderen Aufgabe resultieren, abzuschirmen und um die Verarbeitung multipler Aufgaben zeitlich zu koordinieren. Es wird bis heute debattiert, ob doppelaufgabenbezogene Leistungseinbußen behaviorale Marker für kognitive Kontrolle sind oder ob diese Einbußen lediglich auf strukturelle Limitationen des kognitiven Systems zurückzuführen sind. Diese Limitationen verbieten eine simultane Reaktionsauswahl und führen dazu, dass die Reaktionen für die zwei individuellen Aufgaben einer Doppelaufgabe entsprechend einer „was zuerst kommt, wird zuerst verarbeitet“-Basis ausgewählt werden.

Vor diesem Hintergrund war das Hauptziel der vorliegenden kumulativen Dissertation, die Rolle der kognitiven Kontrolle in Doppelaufgaben erneut zu untersuchen und dabei zum Verständnis der Mechanismen der kognitiven Kontrolle beizutragen, die unserer Fähigkeit zugrunde liegen in einer adaptiven und zielgerichteten Art zu handeln. Hierfür wurden zwei Ebenen der Doppelaufgabenverarbeitung, auf denen kognitive Kontrolle zum Einsatz kommen kann, basierend auf zwei Forschungslinien untersucht.

Die erste Forschungslinie befasste sich mit der lokalen Ebene der Verarbeitung von Doppelaufgaben. Diese Ebene bezieht sich auf die kognitive Verarbeitung der individuellen Aufgaben einer Doppelaufgabe. Um die korrekte Verarbeitung einer individuellen Aufgabe sicherzustellen, kann kognitive Kontrolle über die mentalen Repräsentationen von individuellen Aufgaben, auch Aufgaben-Sets genannt, ausgeübt werden. Um Erkenntnisse über die zugrunde liegenden Mechanismen der lokalen Aufgaben-Set-Kontrolle zu erlangen, wurde die kognitive Verarbeitung in Doppelaufgaben mit der kognitiven Verarbeitung in Aufgabenwechselsituationen in Beziehung gesetzt. Leistungseinbußen, die in Aufgabenwechselsituationen entstehen, werden übereinstimmend als Marker kognitiver Kontrolle interpretiert. Basierend auf der Doppelaufgabenliteratur und den Ergebnissen der Studie I (Hirsch, Schwarzkopp, Declerck, Reese, & Koch, 2016) wurde die parallele

Aktivierung von Aufgaben-Sets in Doppelaufgaben- und Aufgabenwechselsituationen als gemeinsame Basis für ähnliche Mechanismen der kognitive Kontrolle auf der lokalen Ebene von Aufgaben-Sets identifiziert. Um diese kognitiven Kontrollmechanismen zu spezifizieren, wurden in Studie II (Hirsch, Nolden, Declerck, & Koch, im Druck) Korrelationen zwischen den Leistungseinbußen, die in Doppelaufgaben- und Aufgabenwechselsituationen entstehen, analysiert. Die Ergebnisse weisen erstmals darauf hin, dass Leistungseinbußen in Doppelaufgaben, zusätzlich oder anstelle von strukturellen Limitationen, die eine parallele Reaktionsauswahl verhindern, zumindest teilweise kognitive Kontrollprozesse reflektieren, die auch mit aufgabenwechselbezogenen Leistungseinbußen gemessen werden.

Die zweite Forschungslinie adressierte die globale Ebene der Verarbeitung von Doppelaufgaben. Diese Ebene ist nicht auf die kognitive Verarbeitung von ausschließlich einer der beiden individuellen Aufgaben einer Doppelaufgabe beschränkt, sondern bezieht sich auf beide Aufgaben gleichzeitig. Studie III (Hirsch, Nolden, Philipp, & Koch, 2017) lieferte basierend auf einem neuen empirischen Zugang erstmals Evidenz dafür, dass die Identität der individuellen Aufgaben einer Doppelaufgabe gemeinsam in einer separaten mentalen Repräsentation, auch Aufgabenpaar-Set genannt, repräsentiert ist. Dies deutet darauf hin, dass die zwei individuellen Aufgaben einer Doppelaufgabe die Subaufgaben einer komplexeren Einzelaufgabe (z.B. Anfahren mit den zeitlich überlappenden Subaufgaben des Kuppelns und der Gasbetätigung) repräsentieren. Folglich besteht die mentale Repräsentation einer Doppelaufgabe aus multiplen Komponenten, wobei das Aufgabenpaar-Set auf einer hierarchisch höheren Ebene als die subaufgabenspezifischen Aufgaben-Sets organisiert ist. In Studie IV (Hirsch, Nolden, & Koch, 2017) wurde persistierende Aufgabenpaar-Set Aktivierung, die in residualem positivem Priming von Aufgabenpaar-Sets resultiert, als Selektionsmechanismus auf der globalen Ebene der Doppelaufgabenverarbeitung identifiziert.

Insgesamt zeigen die Ergebnisse der vorliegenden Dissertation, dass es multiple Anforderungen an die kognitive Kontrolle während der Verarbeitung von Doppelaufgaben gibt. Kognitive Kontrolle ist nicht nur auf der lokalen Ebene der Doppelaufgabenverarbeitung erforderlich, um die korrekte Verarbeitung der individuellen Subaufgaben sicherzustellen, sondern auch auf der globalen Ebene, um die Auswahl des relevanten Aufgabenpaar-Sets zu ermöglichen. Das Aufgabenpaar-Set gewährleistet wiederum die Spezifikation der individuellen Subaufgaben, die im Rahmen einer Doppelaufgabe bearbeitet werden sollen. Diese neuen Ergebnisse unterstreichen die Wichtigkeit der Berücksichtigung kognitiver Kontrollprozesse in zukünftigen Studien und Modellen zu Doppelaufgaben.

Summary

We frequently perform two tasks in temporal overlap, even though this ordinarily leads to impaired performance of the individual tasks. Such dual-task-related performance costs have been extensively studied in cognitive psychology in order to get insights into the cognitive architecture and the mechanisms of information processing.

The findings have sparked a decades-long theoretical controversy about the role of cognitive control in dual-tasking. Cognitive control enables us to handle complex task demands in a flexible and context-dependent manner and thus to act in a goal-directed way. In dual-task contexts, cognitive control might be required, inter alia, for shielding the processing of each task from interfering influences resulting from the simultaneous processing of another task and for the temporal coordination of multiple task processing. Until today, it is disputed whether dual-task-related performance costs are behavioral markers of cognitive control, or whether they are solely attributable to structural limitations of the cognitive system. These limitations prohibit simultaneous response selection and lead to the situation that the responses for the two individual tasks performed within a dual task are selected on a 'first-come, first-served' basis.

Against this background, the main objective of the present cumulative dissertation was to re-examine the role of cognitive control in dual-tasking, thereby contributing to a better understanding of the mechanisms of cognitive control that underlie our ability to perform in an adaptive and goal-directed manner. To this end, two levels of dual-task processing on which cognitive control might act, namely the local level and the global level of dual-tasking, were investigated based on two lines of research.

The first research line focused on the local level of dual-task processing. This level refers to the cognitive processing of the individual tasks performed within a dual task. To ensure the correct processing of an individual task, cognitive control might act upon the mental representations of individual tasks, which are denoted as task sets. To gain insights into the underlying mechanisms of such local task-set control, dual-task processing was related to cognitive processing in task-switching contexts. The performance costs that arise in task-switching contexts are commonly interpreted as markers of cognitive control. Based on the dual-task literature and the findings of Study I (Hirsch, Schwarzkopp, Declerck, Reese, & Koch, 2016), parallel task-set activation in dual-task and task-switching contexts was identified as a common ground for related mechanisms of cognitive control at the local level of task sets. To specify these related mechanisms of cognitive control, correlations between the performance costs arising in dual-task situations and the performance costs occurring in task-switching contexts were analyzed in Study II (Hirsch, Nolden, Declerck, & Koch, in press). The findings

indicate for the first time that, in addition to or instead of the structural limitations that prohibit parallel response selection, dual-task-related performance costs reflect, at least partly, those cognitive control processes that are also measured by switching-related performance costs.

The second line of research addressed the global level of dual-task processing, which refers to cognitive processing that is linked not only to one of the two individual tasks performed within a dual task but to both individual tasks at the same time. Using a novel empirical approach, the findings of Study III (Hirsch, Nolden, Philipp, & Koch, 2017) provide evidence for the first time that the identity of the individual tasks performed in a dual task is jointly represented in a single mental representation, termed task-pair set. This suggests that the two individual tasks performed in a dual task represent the subtasks of a more complex single task (e.g., starting the car, with the temporally overlapping subtasks of releasing the clutch and accelerating the gas). Consequently, the mental task representation needed for performing a dual task consists of multiple components, including a task-pair set organized at a hierarchically higher-level than the subtask-specific task sets. In Study IV (Hirsch, Nolden, & Koch, 2017), persisting task-pair set activation that results in residual positive priming of task-pair sets was identified as a crucial selection mechanism at the global level of dual-task processing.

In summary, the findings of the present dissertation indicate that there are multiple requirements for cognitive control in dual-tasking. Cognitive control is not only required at the local level of dual-task processing to ensure the correct processing of the individual subtasks but also at the global level to enable the selection of an appropriate task-pair set. The task-pair set, in turn, ensures the specification of the individual subtasks to be performed in a dual task. These novel findings highlight the importance of considering cognitive control processes in future dual-task studies and models.

List of scientific publications and submitted manuscripts

Study I

Hirsch, P., Schwarzkopp, T., Declerck, M., Reese, S., & Koch, I. (2016). Age-related differences in task switching and task preparation: Exploring the role of task-set competition. *Acta Psychologica, 170*, 66-73. doi: 10.10.1016/j.actpsy.2016.06.008

Study II

Hirsch, P., Nolden, S., Declerck, M., & Koch, I. (in press). Common cognitive control processes underlying performance in task-switching and dual-task contexts. *Advances in Cognitive Psychology*.

Study III

Hirsch, P., Nolden, S., Philipp, A. M., & Koch, I. (2017). Hierarchical task organization in dual tasks: Evidence for higher-level task representations. *Psychological Research.* Advance online publication. doi: 10.1007/s00426-017-0851-0

Study IV

Hirsch, P., Nolden, S., & Koch, I. (2017). Higher-order cognitive control in dual tasks: Evidence from task-pair switching. *Journal of Experimental Psychology: Human Perception and Performance, 43*, 569-580. doi: 10.1037/xhp0000309

Please note that the articles do not exactly represent the final version published in *Acta Psychologica*, *Advances in Cognitive Psychology*, *Psychological Research*, and *Journal of Experimental Psychology: Human Perception and Performance*. They are not versions of record and are therefore not suitable for citation.

Declaration of authorship

I hereby certify that this cumulative dissertation has been composed by me and is based on my own work. I conceptualized the studies, conducted the respective experiments, analyzed the data, and wrote the included papers and manuscripts. My supervisors Prof. Dr. Iring Koch and Dr. Sophie Nolden, as well as my colleagues Dr. Tina Schwarzkopp, Dr. Mathieu Declerck, Dr. Andrea M. Philipp, and Prof. Dr. Stefanie Reese, were involved during conceptualization of the studies and also assisted in the constitution of the manuscripts.

1 Introduction

In daily life, we constantly pursue multiple goals at the same time, and for this purpose perform various tasks in temporal overlap. For example, while driving to work, we make phone calls to arrange professional meetings and private appointments. Later, while having lunch during the work break, we answer urgent emails, read papers, or have conversations with colleagues. Finally, in the evening, while preparing dinner, we exchange our experiences of the day with the family and make plans for the next day. These are only a few of a wealth of examples that highlight how often we engage in performing two tasks in temporal overlap, and thus, in dual-tasking. The present cumulative dissertation aims to contribute to the understanding of the mechanisms of cognitive control that underlie our ability to perform successfully in dual-task situations in particular and to behave in an adaptive and goal-directed manner in cognitively highly demanding situations in general.

2 Cognitive control

Cognitive control, also denoted as executive or frontal lobe functions (e.g., Cohen, 2017; Diamond, 2013), is a multidimensional concept encompassing a variety of higher-level cognitive processes. These higher-level cognitive processes select contextually relevant information, monitor, coordinate, and regulate thoughts and behavior in relation to our internal goals by adjusting lower-level sensory, memory, and/or action operations for meeting the current goal requirements (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Logan, 2003; Miller, 2000; Miller & Cohen, 2001). In doing so, these general-purpose cognitive control processes not solely enable us to focus on goal-relevant information, to shield distracting information, and to overcome over-learned behaviors, but they also ensure mental flexibility and allow for adaptive and goal-directed behavior.

2.1 Proactive and reactive control

Cognitive control operates proactively and reactively (dual mechanisms of control framework; Braver, 2012). On the one hand, cognitive control is recruited in a top-down manner to maintain goal-relevant context information prior to the occurrence of an expected cognitively demanding task (i.e., proactive mode). Here, sensory, memory, and/or action operations are biased in a goal-driven manner to prepare and facilitate the processing of an upcoming task (e.g., Miller & Cohen, 2001). For instance, when a bus halts at a roadside stop, and you, as a car driver, anticipate pedestrians crossing the street, cognitive control can act proactively to prepare you for a potential emergency braking.

On the other hand, cognitive control is mobilized in a bottom-up manner to minimize detected difficulties in cognitive processing (i.e., reactive mode; see also Botvinick et al., 2001). With the emergence of such difficulties (e.g. interference), cognitive control is recruited in a just-in-time manner to prevent a fail of achieving our goals. For example, when driving on an otherwise free road you suddenly spot a pedestrian crossing the street in front of your car, cognitive control is recruited reactively to enable an immediate brake.

2.2 Core components of cognitive control

The question as to which specific cognitive processes are encompassed by cognitive control still awaits a generally accepted answer. In the last few decades, a variety of cognitive control processes have been proposed (e.g., Fisk & Sharp, 2004; Hedden & Yoon, 2006). In this regard, working memory (WM) updating, inhibition, and shifting have been most frequently postulated (e.g., Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; see, e.g., Diamond, 2013, for a review).[1]

Updating refers to processes responsible for the monitoring of incoming information for task relevance in order to replace content that is no longer relevant with task-relevant content (e.g., to replace information about traffic rules based on traffic signs). Since information is revised to meet the current goals despite changing environmental demands, updating includes cognitive processes beyond the simple maintenance of information in WM.

Inhibition is dedicated to the suppression of task-irrelevant information and responses (see, e.g., Koch, Gade, Schuch, & Philipp, 2010, for a review). It involves the suppression of memory intrusions that are no longer task-relevant (e.g., not following the usual way to the workplace when there are detour signs), prepotent and automatic responses (e.g., not starting the car when the traffic light is green and pedestrians are still crossing the street; see also Friedman & Miyake, 2004), and task-irrelevant stimuli to the task at hand (e.g., focusing on the traffic lights for the target lane instead of those for the turning lane).

Finally, *shifting* refers to the coordination of cognitive processes, such as WM updating and inhibition (e.g., Best & Miller, 2010), which are required for switching between tasks, operations, and mental states (e.g., switching between accelerating and braking; see, e.g., Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010, for reviews). It is assumed to reflect the ability to disengage and engage tasks, and/or to perform tasks in the face of interference resulting from previous task executions.

[1] The present dissertation does not answer the question of how the cognitive system 'knows' when cognitive control is needed (i.e., homunculus problem). Instead, the dissertation contributes to the understanding of how it acts, thus highlighting the underlying mechanisms of cognitive control.

WM updating, inhibition, and shifting, which have been empirically shown to be related but dissociable (Miyake et al., 2000), form the basis for a variety of studies in the cognitive and clinical domains (see, e.g., Synder, Miyake, & Hankin, 2015, for a review). In numerous of these studies, they were examined in laboratory multitasking contexts.

3 Studying cognitive control in laboratory multitasking contexts

Cognitive control contributes to the pursuit of both short-term goals (e.g., to brake to not exceed the speed limit) and long-term goals (e.g., to save money to buy a car). For the sake of precise performance measurements, the focus in the laboratory, however, ordinarily lies on short-term goals which are often accomplished by a single action and are conceptualized as simple reaction time tasks (e.g., categorizing digits as odd or even).

Task execution is generally assumed to presuppose the activation of an abstract mental representation of the task, termed *task set*, in WM (see, e.g., Kiesel et al., 2010; Monsell, 1996, for a discussion on this concept). A task set is thought to include an organization of task-relevant information (e.g., relevant stimuli and responses, their stimulus-response [S-R] mappings, and task goals) and of cognitive processes needed for task processing from stimulus encoding to responding.[2] The task set, thus, assures the correct execution of a task, and consequently, the achievement of the task goal (e.g., Rogers & Monsell, 1995).

In multitasking situations, we pursue multiple goals under time pressure, thereby performing several tasks, each associated with a separate task set, by rapidly switching between the processing of different tasks (i.e., task switching) and/or by performing tasks simultaneously (i.e., dual-tasking). In both multitasking situations, we hence act in the context of various potentially relevant task sets. To select appropriate task sets (i.e., WM updating), to suppress interfering influences of other task sets (i.e., inhibition), as well as to disengage and engage task sets (i.e., shifting), cognitive control might have to be exercised over task sets in task-switching and dual-task situations.

Owing to these cognitively highly demanding requirements, task-switching and dual-task situations are particularly suitable to study cognitive control. They bring the cognitive system to its limits, evident in performance decrements, whose investigation can give us a window into the mechanisms of cognitive control underlying our ability to handle complex task demands in a flexible and context-dependent manner (see, e.g., Koch, Poljac, Müller, & Kiesel, 2018, for a review).

[2] Task sets can also be defined more formally as a set of parameters that are sufficient to program a model to correctly perform a task (e.g., Logan & Gordon, 2001; Schneider & Logan, 2014; see also Section 3.2.3).

3.1 Task switching

In task-switching contexts, cognitive control is thought to reinforce stability in order to enhance performance when tasks are repeated, and to ensure flexibility in order to improve performance when tasks change (Goschke, 2000). In the laboratory, flexible performance under changing task contexts is often studied based on task-switching paradigms.

3.1.1 Task-switching paradigms

In task-switching paradigms, subjects repeat or switch tasks on a trial-by-trial basis. While doing so, they follow an instructed (i.e., alternating-runs paradigm; e.g., Rogers & Monsell, 1995) or a random task sequence in which cues indicate the forthcoming task to be performed (i.e., cueing-paradigm; e.g., Meiran, 1996). By comparing performance in switch conditions with appropriate non-switch conditions, *alternation costs*, *mixing costs*, and *switch costs* are assessed as switching-related performance impairments (see, e.g., Kiesel et al., 2010; Monsell, 2003; Vandierendonck et al., 2010, for reviews).

3.1.2 Switching-related performance costs as markers of cognitive control

Alternation costs, mixing costs, and switch costs are commonly interpreted as markers of cognitive control processes required in switch conditions but not (or to a lesser degree) in appropriate non-switch conditions. The *alternation cost* is the performance difference between alternating-task conditions, where tasks change after each trial, and single-task conditions, where only one task is performed repeatedly (e.g., Jersild, 1927; Lawo, Philipp, Schuch, & Koch, 2012). Alternation costs represent global performance costs occurring in task-switching situations and are decomposable in mixing costs and switch costs (Meiran, Chorev, & Sapir, 2000), which are considered to measure distinct components of cognitive control (see, e.g., Braver, Reynolds, & Donaldson, 2003; Wasylyshyn, Verhaeghen, & Sliwinski, 2011, for neural and age-related dissociations).

The *mixing cost* is computed by contrasting performance across task repetitions of mixed-task conditions where two tasks are presented intermixed and single-task conditions (e.g., Koch, Prinz, & Allport, 2005; Rubin & Meiran, 2005). This cost is assumed to mainly reflect WM processes of task-set maintaining and updating (e.g., Mayr, 2001; Pettigrew & Martin, 2016; for a discussion about the role of interference resolution, see Section 4.1.1).

Switch costs, calculated as the performance difference between switch trials and repetitions trials of mixed-task blocks (e.g., Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995), are presumed to predominantly measure the shifting component of cognitive control

(Miyake et al., 2000). This is because in switch trials task sets are required to be disengaged and engaged, whereas in repetition trials a task set can be applied again.

Both mixing costs (e.g., Jost, Mayr, & Rösler, 2008; Rubin & Meiran, 2005) and switch costs (e.g., Koch, 2003; Koch & Allport, 2006) have been shown to be reduced with preparation time, presumably indicating the involvement of proactive control processes responsible for bringing the cognitive system to a state of readiness to repeat or change a task in task-switching contexts (see Karayanidis & Jamadar, 2014, for a review). Preparation, however, usually does not eliminate performance costs completely, even with ample preparation time, resulting in residual performance costs (mixing costs: e.g., Rubin & Meiran, 2005; switch costs: e.g., Nieuwenhuis & Monsell, 2002). These residual costs suggest the recruitment of reactive control processes after the stimulus onset (e.g., Karayanidis & Jamadar, 2014). The task-switching paradigm, thus, represents an experimental tool for studying both proactive and reactive control underlying flexible and adaptive behavior.

3.1.3 Models of cognitive control in task switching

Numerous models of cognitive control in task switching have been put forward which also attempt to account for reduced switching-related performance costs and residual costs with preparation. Most of them are assignable to *task-set reconfiguration models* (e.g., Meiran, 1996; Rogers & Monsell, 1995; Rubinstein, Meyer, & Evans, 2001) and to *proactive interference models* (e.g., Allport et al., 1994; Allport & Wylie, 1999, 2000).

According to *task-set reconfiguration models*, a task set has to be activated in WM to perform a task (e.g., Rogers & Monsell, 1995). When the task switches, the task set has to be reconfigured in accordance with the new task because it is structurally impossible that two task sets are activated simultaneously. There are multiple proposals regarding what exactly the reconfiguration, and thus, what the activation of a task set entails (e.g., goal shifting: Rubinstein et al., 2001; stimulus-set biasing: Meiran, 2000; retrieval of S-R mappings from long-term memory, LTM: Mayr & Kliegl, 2000). The proposals strongly depend on the underlying definition of a task set, but what they have in common is the replacement of a previously relevant task set by a currently needed one.

The reconfiguration processes are posited to occur at two stages. An initial endogenous stage (e.g., goal shifting, Rubinstein et al., 2001) starts as soon as the response for the previous task is executed and the identity of the upcoming task is known. It hence offers an opportunity to prepare for the next task, thereby reducing switch costs. A second exogenous stage (e.g., activation of S-R mappings, Rubinstein et al., 2001) follows the onset of the target stimulus,

leading to residual switch costs. When a task has to be repeated, the already activated task set is applied again, so that no task-set reconfiguration is required. Hence, in this model, switch costs primarily index the duration of an additional processing stage for cognitive control processes required to reconfigure a task set when a task changes.

In contrast to task-set reconfiguration models, *proactive interference models* assume that switch costs are caused by task-set inertia (e.g., Allport et al., 1994). The core idea is that once a task set has been activated, its activation persists even after task execution. When the task switches, the persisting activation (positively) primes the prior task set, eliciting interference between the currently relevant task set and the previous task set. Additional interference arises due to the prior inhibition of the currently intended task set (or components thereof), which results in negative priming of this task set (see, e.g., Koch et al., 2010, and D'Angelo, Thomson, Tipper, & Miller, 2016, for reviews on inhibition and negative priming).

From this theoretical perspective, reduced switch costs with preparation time are caused by the decay of task-set activation and inhibition over time. Some additional interference, however, has to be overcome when the target stimulus is presented and leads to residual switch costs. Therefore, switch costs should primarily reflect the time needed to overcome persisting task-set activation and inhibition in order to perform a new task which prolongs task-specific processes like the selection of responses.

Task-set reconfiguration models and proactive interference models are not mutually exclusive and have therefore been sought to be integrated (e.g., Ruthruff, Remington, & Johnston, 2001; Yeung & Monsell, 2003). Accounts that consider both task-set reconfiguration and task-set inertia can explain a variety of empirical phenomena observed in task-switching research (see, e.g., Vandierendonck et al., 2010, for a review).

3.2 Dual-tasking

In addition to task-switching contexts, cognitive control might also be essential in dual-task situations. When two tasks are performed in temporal overlap, cognitive control is possibly needed for shielding the processing of each task from the interfering influences of the other task and for the temporal coordination of multiple task processing. The reliance of dual-tasking on cognitive control can be studied in the laboratory using dual-task paradigms.

3.2.1 Dual-task paradigms

In dual-task paradigms, such as the psychological refractory period (PRP) paradigm (e.g., Telford, 1931; Welford, 1952; see, e.g., Pashler, 1994, for a review), subjects perform

two tasks, Task 1 (T1) and Task 2 (T2), each associated with a separate stimulus and response, in temporal overlap, thereby usually responding firstly to the stimulus for T1 (S1) and then to the stimulus for T2 (S2; see, e.g., Ferreira & Pashler, 2009; Hirsch, Declerck, & Koch, 2015, for the use of the PRP procedure in linguistic studies). In such dual-task conditions, the degree of temporal overlap in task processing is determined by the time interval between the presentation of S1 and the onset of S2 (stimulus onset asynchrony, SOA). With short SOAs, there is a strong temporal overlap in T1 and T2 processing, whereas with long SOAs, task processing overlaps temporally to a lesser degree. By comparing performance across conditions that require different degrees of temporally overlapping task processing, various dual-task-related performance decrements can be explored.

3.2.2 Dual-task-related performance costs as markers of cognitive control

Extensively studied dual-task-related performance costs are represented by the PRP effect and dual-task costs. The *PRP effect* refers to worse T2 performance in dual-task conditions with short SOAs compared to dual-task conditions with long SOAs (e.g., Janczyk, Pfister, Hommel, & Kunde, 2014; Schubert, 1999; see Pashler, 1994, for a review). *Dual-task costs* are ordinarily computed by comparing T2 performance in dual-task conditions with long SOA with performance in single-task blocks, where subjects perform only one task (see Halvorson, Ebner, & Hazeltine, 2013, for a discussion on the calculation of dual-task costs).

In contrast to switching-related performance costs, there is so far no consensus about the underlying cognitive mechanisms of dual-task-related performance costs, as it will become apparent in the following presentation of cognitive control models in dual-tasking. In the present dissertation and therefore also in the following description of the dual-task models a special focus is placed on the PRP effect.

3.2.3 Models of cognitive control in dual-tasking

Various models have been proposed to account for dual-task-related performance costs. Most of these models can be categorized as *structural response-selection bottleneck (RSB) models* (e.g., Telford, 1931; Welford, 1952; see, e.g., Pashler, 1994, for a review), *capacity sharing models* (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2003), and *strategic T2 deferment models* (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997a, 1997b).

Structural RSB models hold that the processing of each task entails discrete successive processing stages, comprising a perceptual stage (i.e., stimulus encoding), a response-selection stage (i.e., translation of the stimulus to its response), and a motor stage (i.e., response

execution). Whereas processing at perceptual and motor stages can proceed for two tasks in parallel, there is a structural all-or-none processing bottleneck at the response-selection stage which prevents parallel response selection for two tasks (see Pashler, 1994, for a review; see also Broadbent, 1958). Which of the two tasks gets first access to this bottleneck is determined on a 'first-come, first-served' basis, superseding cognitive control for task shielding and the coordination of temporally overlapping task processing (see Figure 1A).

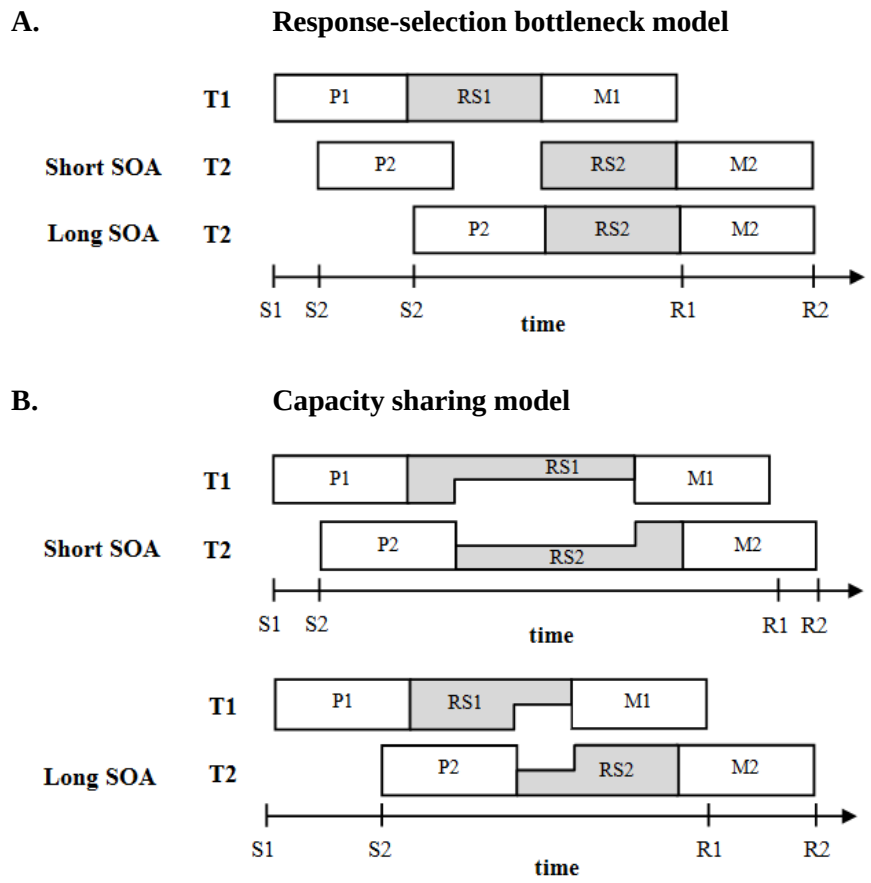

Figure 1. Visualization of the response-selection bottleneck model (adapted from Pashler, 1994; top panel A) and the capacity sharing model (adapted from Tombu & Jolicoeuer, 2003; bottom panel B). P1 and P2 = perceptual processing stage for Task 1 (T1) and Task 2 (T2); RS1 and RS2 = response-selection stage for T1 and T2; M1 and M2 = motor stage for T1 and T2. The time line between Stimulus 1 (S1) and Response 1 (R1) and between Stimulus 2 (S2) and Response 2 (R2) represents the reaction time for T1 and T2.

With short SOAs, perceptual processes start and finish for both tasks almost simultaneously, which is why T2 processing is held in a passive queue until the T1 response is selected (i.e., cognitive slack; Schweickert, 1978). With long SOAs, T2 perceptual processing proceeds concurrently with T1 response selection reducing the waiting time for the availability of the response-selection bottleneck after the completion of perceptual processing in T2. T2 performance is, thus, worse with short than long SOAs, resulting in the PRP effect.

As opposed to structural RSB models, *capacity sharing models* posit that responses can be selected simultaneously for two tasks, but that there is a limited processing capacity at the stage of response selection which has to be allocated in a graded manner to both tasks (e.g., Lehle & Hübner, 2009; Navon & Miller, 2002; Tombu & Jolicoeur, 2003; see also Kahneman, 1973). The processing rate of a task is determined by the amount of capacity allocated to a task. With short SOAs, the capacity has to be shared for a longer time period than with long SOAs, resulting not only in a PRP effect but also in worse T1 performance with short compared to long SOA (see Figure 1B).

Structural RSB models and capacity sharing models are premised on some sort of capacity sharing across tasks, but they differ with regard to the proposed capacity sharing mechanism. Whereas structural RSB models assume an all-or-none sharing mechanism so that capacity is fully allocable either to T1 or to T2, capacity sharing models suppose a graded capacity sharing mechanism which allows for parallel task processing at the response-selection stage. These are strong notions about the cognitive architecture. However, the specific structural underpinnings leading to these limitations remain unclear in these models.

In contrast to structural RSB models and capacity sharing models, *strategic T2 deferment models*, such as the executive-process/interactive-control (EPIC) architecture (Meyer & Kieras, 1997a, 1997b) and the executive control of visual attention (ECTVA) model (Logan & Gordon, 2001), assume that dual-task-related performance costs do not result from a structural response-selection bottleneck or a limited processing capacity at the response-selection stage per se but from a strategic decision for sequential response selection. In both models, serial response selection is expected to prevent unwanted response reversals.

In the computational *EPIC architecture*, cognitive control is conceptualized by an executive process rule set and the T1 and T2 task sets as two separate production rule sets, including the task goal and the if-then rules needed to perform a task (Meyer & Kieras, 1997a, 1997b). To meet the current instructions, the executive process rule set coordinates the production rule sets. The executive process rule set defines, in addition to the point in time when T1 and T2 processing are allowed to start, lock-out points in T2, where T2 processing is suspended, and lock-in events in T1, which allow T2 processing to continue (see Figure 2). These lock-out points and lock-in events can be flexibly set at perceptual stages, response-selection stages, and motor stages, depending on instructions and experimental conditions.

In PRP settings, which prioritize T1 over T2 processing, T1 processing is allowed to immediately proceed to the response execution stage, whereas T2 response execution is deferred by setting the lock-out point, for example, after T2 response selection. This ensures

that with short SOAs T1 processing has progressed adequately to produce the T1 response before the T2 response.[3] Thus, according to the EPIC architecture, the PRP effect is the result of strategic deferments of T2 processing.

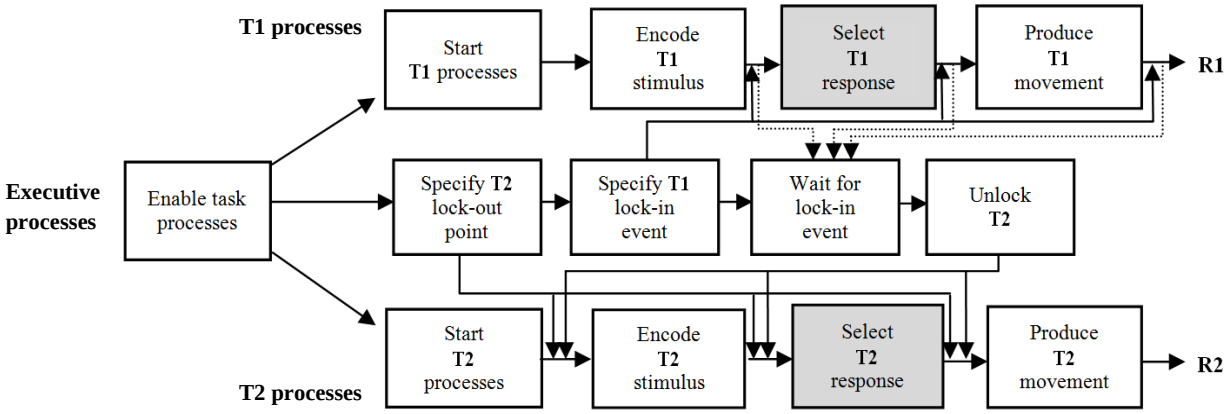

Figure 2. Visualization of the executive-process/interactive control (EPIC) architecture in dual-task contexts (adapted from Schumacher et al., 1999). T1 = Task 1; T2 = Task 2; R1 = response in T1; R2 = response in T2.

A strategic deferment of T2 processing is also proposed in the *ECTVA model* (Logan & Gordon, 2001). This computational model attributes serial response selection for T1 and T2 to functional constraints emerging in the cognitive system when the same capacity is employed for distinct aims by multiple processes (Feng, Schwemmer, Gershman, & Cohen, 2014; Fischer & Plessow, 2015). These constraints refer to the problem that it is harder for the cognitive system to figure out which response is associated with which task when responses are selected simultaneously for two tasks (i.e., dual-task binding problem). The model, however, does not assume that parallel response selection is structurally impossible.

The ECTVA model incorporates subordinate processes that can be programmed to perform a particular task (i.e., T1 or T2), and executive processes that program these subordinate processes. The operating principles of the subordinate processes at the response-selection stage are described based on a combination of the *theory of visual attention* (TVA; Bundesen, 1990) and the *exemplar-based random walk* (ERBW; Nosofsky & Palmeri, 1997). TVA selects stimuli and categorizes them along the attributes relevant for the current task. Its categorizations are accumulated in response counters of the ERBW.

[3] In the case of highly practiced T1 and T2 combinations, in place of this lock-out scheduling strategy, the EPIC architecture can follow an interleaved scheduling strategy. Under this strategy, an executive process rule set which is highly specific to a certain combination of T1 and T2 allows T1 and T2 to be predominantly processed simultaneously. The processing of a task is only suspended for minimal time periods in which parallel task processing would lead to unavoidable conflicts between T1 and T2. Since in the present dissertation the effect of training on dual-task performance was not explored, this strategy is not further addressed.

TVA is run based on a task set. In the ECTVA framework, a task set is defined as a set of control parameters sufficient to program TVA to perform a particular task. Task sets differ across tasks in the number of control parameters and the values they take. They are represented at two levels—the task level and the parameter level. The task-level task set is a propositional representation of task instructions and is held in WM. The parameter-level task set contains a set of TVA control parameters derived from the task-level task set (see Figure 3). It is held in WM, and after being transmitted to TVA, it also resides in TVA.

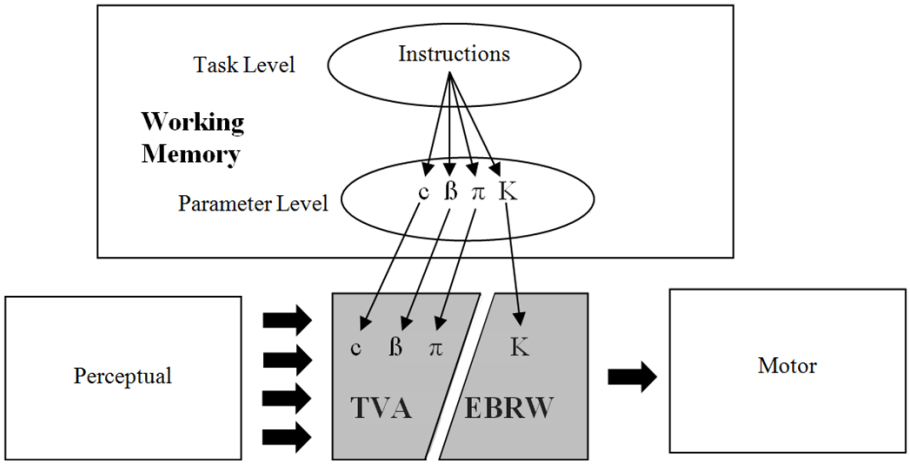

Figure 3. Visualization of the executive control of visual attention (ECTVA) model (adapted from Logan & Gordon, 2001). Stimulus and response selection rely on the *theory of visual attention* (TVA; Bundesen, 1990) and the *exemplar-based random walk* (ERBW; Nosofsky & Palmeri, 1997). To perform a task, a parameter-level task set consisting of feature-catch (c) parameters, bias (β) parameters**,** priority (π) parameters, and difference threshold (K) parameters has to be derived from the task-level task set and transmitted to the TVA.

The parameter-level task set controls stimulus and response selection based on feature-catch (c) parameters, priority (π) parameters**,** bias (β) parameters, and difference threshold (K) parameters. The c parameter defines the attentional scope. For example, you might perceive this page holistically, taking into account different aspects of the page, such as the structure of the text. However, it is also possible to focus on a certain paragraph, a word, or even a letter on this page (Hommel, Brown, & Nattkemper, 2016). The π parameter represents the relevance of selecting stimuli with specific characteristics, and the β parameter biases TVA to categorize these stimuli (or their attributes) towards certain response categories. Finally, the K parameter determines how many counts K more a response counter has to accumulate than another to allow the selection of the response associated with the counter.

Model simulations showed dual-task performance to be better when TVA is run twice, once for each task, than when it is run for T1 and T2 in parallel. Therefore, in dual-task

situations, first a parameter-level task set favouring stimulus and response selection in T1 is transmitted to TVA. In this parameter-level task set, for instance, the π parameters (e.g., left stimulus) and β parameters (e.g., odd vs. even) for T1 are set high, whereas the π parameters (e.g., right stimulus) and β parameters (e.g., smaller vs. larger than 5) for T2 are set low. As a result, TVA categorizations can be easily attributed to the prioritized T1.

Before TVA runs for T2, the random walk counters of the ERBW are inhibited (i.e., reset to a specific percentage of their values) because otherwise the selected response counter for T1 would still have *K* more counts than any other counter and would therefore be selected again (i.e., serial order problem). To select a response for T2, a parameter-level task set specifying the control parameters to program TVA to perform T2 is transmitted to TVA. In this task set, π parameters and β parameters are set high for T2 and low for T1.

Consequently, the ECTVA model is a serial response-selection model that mimics capacity sharing models by including parameters relevant for T2 in the parameter-level task set for T1. It, however, differs, from capacity sharing models in the sense that the progress of T2 processing during T1 processing is due to the inhibition of response counters lost after T1 response selection (see Logan & Gordon, 2001). According to the ECTVA model, the PRP effect is attributable to the strategic decision to run the TVA twice based on separate parameter-level task sets for T1 and T2 in order to distinguish in an easier manner which response goes with which task. As a result, at short SOAs, the transmission of the T2 parameter-level task set has to wait longer to begin than with long SOAs.

Overall, it can be conlcuded that the reviewed dual-task models differ with regard to whether they attribute the PRP effect to structural limitations of the cognitive system or to a strategic decision for serial response selection (see Fischer & Plessow, 2015, for a review). The empirical differentiation between these models has proved to be difficult.

3.3 Theoretical controversy about the role of cognitive control in dual-tasking

Whereas switching-related performance costs are commonly attributed to time-consuming and error-prone cognitive control processes, there is a longstanding theoretical controversy about the role of cognitive control in dual-tasking (see, e.g., Koch et al., 2018; Schubert, 2008, for reviews). It has been a decades-long dispute as to whether the PRP effect reflects cognitive control processes, or whether this effect is merely the result of a structural limitation of the cognitive system which passively queues response selection based on a 'first-come, first-served' strategy for one of the two tasks. Such strategy would supersede cognitive control for task shielding and the coordination of temporally overlapping task processing.

In this regard, almost two decades ago, Pashler (2000) adopted a position that has influenced both empirical approaches and theorizing in dual-task research. He argued that switching-related performance costs and dual-task-related performance costs have distinct sources, meaning that switching-related performance costs are markers of cognitive control, whereas the PRP effect does not reflect cognitive control processes. To date and thus almost 20 years of dual-task research later, his assumption could still not be empirically validated or invalidated. Against the background of this theoretical controversy, the main objective of the present cumulative dissertation was to re-examine the role of cognitive control in dual tasks.

4 Empirical findings of the present dissertation

Within the scope of the present dissertation, four studies were conducted to explore the role of cognitive control in dual-tasking. A first research line focused on cognitive control at the local level of dual-task processing (i.e., Study I and II), whereas a second research line addressed cognitive control at the global level of dual-task processing (i.e., Study III and IV).

The *local level of dual-task processing* refers to the processing of an individual task which is performed in temporal overlap with another task. Cognitive control might be exerted on the task sets of individual tasks in order to guide the processing of an individual task from stimulus encoding to response execution. The dual-task-related performance costs and the dual-task models reviewed so far focus on this local level of task-set control.

The *global level of dual-task processing* is not specific to one of the individual tasks performed in a dual task but is related to both individual tasks at the same time. The present dissertation addressed the question of whether the identity of the two tasks to be performed in a dual task is cognitively represented jointly in a single mental representation, henceforth called task-pair set. Such task-pair sets would indicate that T1 and T2 are subtasks of a more complex and hierarchically higher-level single task, such as starting a car with the temporally overlapping subtasks of releasing the clutch and accelerating the gas. Cognitive control could then, in addition to task sets, act on task-pair sets to ensure the selection of an appropriate task-pair set, which defines the relevant subtasks of a dual task.

In the first research line, cognitive processing in dual tasks was related to that in task switching, where performance is generally assumed to depend on cognitive control. First, comparable processing requirements which might provide a common ground for related mechanisms of task-set control in task-switching and dual-task contexts were identified (cf. Study I). Based on a within-subject cross-paradigm correlation analysis, dual-task-related performance costs were subsequently compared with switching-related performance costs to

specify shared underlying cognitive control mechanisms (cf. Study II). In the second research line, a novel empirical approach was developed to investigate whether the identity of T1 and T2 is represented in the form of a task-pair set (cf. Study III), and if so, which selection mechanism acts at the global level of these task-pair sets (cf. Study IV).

4.1 Cognitive control at the local level of dual-tasking

Notwithstanding the common research subject in terms of cognitive mechanisms underlying multitasking performance, dual-task and task-switching studies have so far mainly followed independent research lines with separate research questions, empirical approaches, and paradigm-specific models (for exceptions see, e.g., Band & van Nes, 2006; Oriet & Jolicoeur, 2003; Pashler, 2000; Sigman & Dehaene, 2006; see Band, Jolicoeur, Akyürek, & Memelink, 2006; Koch et al., 2018, for integrative reviews). Due to these paradigm-specific approaches, both research lines to date have advanced our understanding of the cognitive architecture primarily independently of each other.

Whereas switching-related performance costs are commonly interpreted as markers of cognitive control, there is so far no convincing empirical evidence for the reliance of dual-task-related performance costs on cognitive control. Against this background, it might be interesting to see whether there are comparable requirements on cognitive processing at the local level of task sets across task-switching and dual-task situations. This is an important question because comparable cognitive processing requirements possibly necessitate related mechanisms of cognitive control to be handled.

4.1.1 Common ground for related mechanisms of task-set control in dual-tasking and task switching

A common ground for related cognitive control mechanisms in task-switching and dual-task contexts might be parallel task-set activation. To shed light on whether task sets are activated to some extent simultaneously during task switching and dual-tasking, it is useful to induce additional competition between tasks by increasing the degree to which task sets overlap. The degree of task-set overlap is determined by the stimulus and response valence (e.g., Mayr, 2001). Univalent stimuli and responses are associated with one task only. Bivalent stimuli are linked to both tasks, and thus, also afford the application of the competing task. In the same vein, responses are bivalent, when the response specifications for both tasks overlap conceptually (e.g., tasks are mapped onto different hands but with the same spatial mapping) or physically (e.g., same effectors and keys).

When both task sets are activated to some degree simultaneously during task switching and dual-tasking, there should be stronger interference between their S-R mappings with overlapping than with non-overlapping tasks sets. Hence, overlapping task sets should impose higher demands on between-task interference resolution than non-overlapping task sets, thereby hampering multitasking performance. However, increased performance costs with overlapping compared to non-overlapping task sets do not have to necessarily indicate that task sets are continuously activated simultaneously in WM. The onset of an additional stimulus in dual tasks and the display of a stimulus which, in addition to the intended task, is associated with another task in task-switching contexts could also just prime in a bottom-up manner the irrelevant task set due to its storage in LTM (e.g., Kiesel, Wendt, & Peters, 2007).

In *task-switching research*, overall performance has been shown to be usually worse with overlapping task sets than with non-overlapping task sets (e.g., Spector & Biedermann, 1976). More importantly, the effect of task-set overlap is typically stronger in switch trials than in repetition trials (e.g., Meiran, 2000, 2008), and in repetition trials than in single-task trials (e.g., Koch et al., 2005; Rubin & Meiran, 2005), resulting in increased performance costs with overlapping than less overlapping task sets.

Elevated *switch costs* with overlapping task sets per se do not provide conclusive evidence for parallel task-set activation. They might solely indicate that the irrelevant task set is strongly activated due to its prior application, and that task switching might be more difficult when there is additional competition between tasks induced by overlapping task sets.

However, increased *mixing costs* with overlapping task sets suggest that in contrast to single-tasks, in task repetitions, the irrelevant task set is active to some extent along with the relevant one (see Philipp, Kalinich, Koch, & Schubotz, 2008). When irrelevant task sets are completely deactivated, task repetition performance should not differ depending on whether task sets overlap or not. Thus, task-set reconfiguration and resolution of proactive interference do not seem to be an all-or-none process, enabling some parallel task-set activation.

Study I (Hirsch, Schwarzkopp, Declerck, Reese, & Koch, 2016) of the present cumulative dissertation provides additional, albeit indirect, evidence for parallel task-set activation during task switching. In this study, old adults (i.e., 65 years and above) and young adults (i.e., below 30 years) performed single-task conditions and alternating-task conditions. Owing to the switch requirement in each trial, alternating-task conditions induce, in comparison with mixed-task conditions, stronger between-task interference. At the same time, the predictable task sequence offers the possibility to prepare for the upcoming task thereby reducing between-task interference before stimulus onset.

In *Experiment 1*, task sets overlapped at the response level (i.e., conceptual response-set overlap) but not at the stimulus level. In addition to alternation costs, we found improved performance with long than with short preparation time (i.e., response-stimulus interval, RSI) and more so in alternating-task conditions than in single-task conditions, resulting in a preparatory reduction of alternation costs. In *Experiment 2*, we replaced the non-overlapping stimulus set by an overlapping one and replicated the findings of Experiment 1.

By comparing performance across these experiments, we showed that alternation costs and their preparatory reduction were more marked with overlapping than with non-overlapping stimulus sets, and that age-related differences in the preparatory reduction of alternation costs were larger with overlapping than with non-overlapping stimulus sets. In particular, old and young adults showed a comparable preparatory reduction of alternation costs with non-overlapping stimulus sets, whereas with overlapping stimulus sets, the preparatory reduction was smaller for old than for young adults.[4]

It is well-documented in cognitive aging research that aging is accompanied by a performance decline in various cognitive tasks, especially those requiring cognitive control (see, e.g., Salthouse, 2010, for a review). Regarding the effect of age on task-switching performance, it has been shown that there are usually no age-related differences in switch costs, indicating intact shifting processes in old age (e.g., Hartley, Kieley, & Slabach, 1990). Mixing costs, however, are ordinarily larger in old than in young adults (e.g., Reimers & Maylor, 2005), suggesting a WM updating deficit in old age (i.e., age-related dissociation; see Verhaeghen & Cerella, 2002; Wasylyshyn et al., 2011, for a review and a meta-analysis).

Note that the alternation costs assessed in Study I reflect a mixture of shifting and WM updating processes. Considering the age-sensitivity of mixing costs and the age-insensitivity of switch costs, it can be argued, however, that the observed age-related effects in the preparatory reduction of alternation costs were caused by impaired preparatory task-set updating processes in old age. From cognitive aging research, it is well known that there is an age-related decline in the distractor interference resolution ability (e.g., Lustig & Jantz, 2015; Pettigrew & Martin, 2014), and in line with this age-related decline, it has been shown that the age-related increase in mixing costs is especially strongly pronounced with overlapping task sets (Mayr, 2001). This suggests that in task repetitions, the irrelevant task set is active to some extent along with the relevant one and that due to an age-related decline in the distractor interference resolution ability old adults suffer more than young adults from the activation of the irrelevant task set during task-set maintaining and updating. In the light of these findings, the age-related decline

[4] Note that all age-related effects reported in the present dissertation were controlled for general slowing.

in the preparatory reduction of alternation costs found in Study I might indicate that the reliably observed age-related increase in mixing costs might be partly due to impaired preparatory processes involved in the updating and maintaining of interfering, and thus, simultaneously activated task sets in repetition trials (see also Lawo et al., 2012).

It is important to note that differences in the degree of task-set overlap might be linked to differences in WM requirements. In contrast to interfering overlapping task sets, non-overlapping task sets might have encouraged the construction of a single representation comprising the task sets for both tasks (e.g., Kleinsorge, 2004; Kleinsorge & Heuer, 1999; Kleinsorge, Heuer, & Schmidtke, 2001) and making task-set updating less necessary.

A methodologically improved index of parallel task-set activation is, therefore, represented by *response congruency effects* (e.g., Sudevan & Taylor, 1987). These effects are measured with fully overlapping task sets as worse performance in incongruent trials, where a stimulus activates different responses in the relevant task and the irrelevant task, relative to congruent trials, where a stimulus activates the same response in both tasks. Congruency effects are typically larger in repetition trials than in single-task trials (e.g., Meiran & Kessler, 2008). This indicates that responses according to irrelevant task sets are activated to a certain degree simultaneously with the relevant one, necessitating some sort of interference resolution (cf., Rubin & Meiran, 2005) even in task repetitions, where no direct carry-over effects of the irrelevant task-set activation due to its prior application occur. However, response congruency effects were very weak in Study I (i.e., only a main effect in the error rates), as a result we could not look into this methodological improved measure of parallel task-set activation.

Dual-task research followed a similar empirical approach to study parallel task-set activation. The use of overlapping response sets allows for a comparison of dual-task performance across conditions where S1 and S2 activate a conceptually or physically same response (i.e., compatible) and where they activate different responses (i.e., incompatible). The effects of interest are the *forward response-response (R-R) compatibility effect* and *the backward R-R compatibility effect*. Worse performance with incompatible R-R relations than compatible R-R relations measured in T1 is referred to as backward R-R compatibility effect, and that assessed in T2 as forward R-R compatibility effect (e.g., Fischer & Dreisbach, 2015; Hommel, 1998; Koch & Prinz, 2002; Miller, 2006; Schuch & Koch, 2004; see also Schubert, Fischer, & Stelzel, 2008). These effects indicate that during response selection for a task, the task set of the other task, or its components, are activated to some degree simultaneously. This is because task performance should not differ depending on whether the other task requires the same or a different response when its task set would be deactivated.

Parallel task-set activation, measured as backward R-R compatibility effect, poses a challenge to RSB models which state that it is structurally impossible for response selection to proceed for T1 and T2 in temporal overlap. Inspired by this effect, different modifications of this model, all maintaining the idea of a response-selection bottleneck and proposing an additional automatic stage of response activation between perceptual processing and the final response selection have been developed (e.g., Hommel, 1998; see also Janczyk, Renas, & Durst, 2017; Lien & Proctor, 2002). At the response-activation stage, a response has to reach a certain threshold before it can be selected at the response-selection stage. With short SOAs, the response-activation stages overlap for T1 and T2, and/or the T2 response-activation stage overlaps with the T1 response-selection stage, thus enabling the T2 to affect T1 processing.

In sum, it can be concluded that in both task-switching and dual-task contexts, there is empirical evidence for parallel task-set activation. Such parallel task-set activation provides a solid ground for related mechanisms of cognitive control in task switching and dual-tasking.

4.1.2 Related mechanisms of task-set control in dual-tasking and task switching

Whether successful performance in the face of simultaneously activated and thus competing task sets in task switching and dual-tasking is ensured by related mechanisms of task-set control was explored in ***Study II (Hirsch, Nolden, Declerck, & Koch, in press)***. In this study, we analyzed within-subject correlations between the performance costs arising in highly comparable task-switching and dual-task paradigms. To ensure comparability across the paradigms, we designed the task-switching and dual-task paradigms as similarly as possible using the same stimuli, tasks, responses, task sequences (i.e., unpredictable task sequence with task switches and repetitions), and durations of critical time intervals (i.e., RSI and SOA). We ran a single experiment, including a dual-task part and a task-switching part.

In the dual-task part, there were, besides dual-task costs and the PRP effect, switch costs in T2 (i.e., T2 performance in T1-T2 switch trials where different tasks are performed as T1 and T2 vs. T2 performance in T1-T2 repetition trials where the same task is performed as T1 and T2; see also Band & van Nes, 2006; Lien, Schweickert, & Proctor, 2003), suggesting that dual-tasking relies on the shifting component of cognitive control, at least when different tasks are performed as T1 and T2. Moreover, we found response-repetition benefits in T2 (i.e., across T1 and T2; forward R-R compatibility effects) of T1-T2 repetition trials and response-repetition costs in T2 of T1-T2 switch trials. In the task-switching domain, different explanations which can be transferred to parallel task processing have been put forward to account for response-repetition effects.

Response-repetition effects might, for example, indicate that T1 responses are inhibited after their execution to prevent response perseveration in T2 (i.e., inhibition account; e.g., Druey, 2014; Druey & Hübner, 2008). Response repetitions in T2 of T1-T2 repetitions are accompanied by a stimulus-category repetition which might prime the inhibited response and thus weaken the inhibitory aftermath, thereby leading to a response-repetition benefit. In T2 of T1-T2 switches, a response repetition does not come along with a stimulus-category repetition so that the inhibition has to be overcome, resulting in response-repetition costs.

In contrast, according to episodic binding accounts, task execution strengthens the binding (i.e., association) between the current response (e.g., right key) and a task-specific stimulus category (e.g., < 5; e.g., Altmann, 2011; Schuch & Koch, 2010). In T1-T2 repetition trials with response repetitions, the binding between responses and stimulus categories formed in T1 is reapplied in T2, leading to positive response-repetition priming. In T1-T2 switch trials with response repetitions, however, the response has to be bound to another stimulus category, leading to response-repetition costs in T2 of T1-T2 switch trials.

Finally, it is also possible to combine these accounts, as recently proposed by Koch, Frings, and Schuch (2018). According to this hybrid account, response-repetition benefits in T2 of T1-T2 repetitions are mainly due to episodic bindings and response-repetition costs in T2 of T1-T2 switches are mainly due to the carryover effects of T1 response inhibition.

Thus, two important conclusions can be derived from the findings of the dual-task part. First, dual-task performance, at least in the case of T1-T2 switch trials, relies on the shifting component of cognitive control; and second, T1 response inhibition and/or episodic binding might play a role in dual-tasking. Importantly, since switch costs in T2 and the response-repetition effects were of comparable magnitude across SOAs, these cognitive processes contribute to dual-task performance, but they act independently of the mechanisms leading to the PRP effect. Assuming sequential response selection, these processes should occur after response selection for T1 and before that for T2.

Further conclusions about cognitive control in dual-tasking can be derived from a correlation analysis between dual-task-related performance costs and the performance costs assessed in the task-switching part. In the task-switching part, we observed substantial mixing costs and switch costs. The overall performance was worse with short than long RSI, but the mixing costs and switch costs did not differ in their size across the RSIs.

The correlation analysis showed relationships between switch costs in the task-switching part, switch costs in T2, and the PRP effect. The correlations remained surprisingly substantial even when using only T1-T2 repetition trials for the calculation of the PRP effect.

First, the correlation between switch costs in the task-switching part and switch costs in T2 in the dual-task part (r = .64) supports the conclusion that shifting processes play a crucial role in dual-tasking, at least when different tasks are used as T1 and T2. Second and most important against the background of the controversy about the reliance of the PRP effect on cognitive control, the correlations between the PRP effect (i.e., averaged over T1-T2 switches and repetitions) and switch costs in T2 (r = .60) and between the PRP effect (i.e., averaged over T1-T2 switches and repetitions) and switch costs in the task-switching part (r = .63) suggest that the PRP effect at least partly reflects cognitive control processes, namely those that are also isolated when contrasting performance across task switches and repetitions. As indicated by the correlations between the PRP effect in T1-T2 repetition trials and switch costs in T2 (r = .60) and between the PRP effect in T1-T2 repetition trials and switch costs in the task-switching part (r = .59), the cognitive control processes reflected by switch costs seem to contribute to the PRP effect even when the task is repeated across T1 and T2.

Given that switch costs in the task-switching part and the dual-task part are markers of the shifting component, the correlations between switch costs in the task-switching part, switch costs in T2 of the dual-task part, and the PRP effect might indicate that the shifting component contributes to the PRP effect. These correlations cannot be accounted for by a task-set reconfiguration stage located between the response-selection stages of T1 and T2, as proposed in the modified RSB model by Lien and colleagues (2003). Since task-set reconfiguration occurs with both short and long SOAs, the impact of the shifting processes on dual-task performance is averaged out when computing the PRP effect. Consequently, these correlations should reflect cognitive control processes that occur largely with short compared to long SOA, or with short SOA but not with long SOA. A possible explanation in this regard might be that responses are not selected in a strict sequential manner for T1 and T2, but that some kind of rapid switching between different components of the T1 and T2 task sets is necessary to perform these tasks in temporal overlap (see Duncan, 1995, for a similar notion).

In task-switching research, switch costs, however, have not only been interpreted in the light of the shifting component but also in relation to the inhibition component. In this context, it has been shown that irrelevant task sets or their components are inhibited during response selection for the relevant task (e.g., Philipp, Jolicoeur, Falkenstein, & Koch, 2007; Schuch & Koch, 2003; see also Section 4.2.2).

Accordingly, it is conceivable that the onset of S2 triggers the activation of the T2 task set, and that the activation of the T2 task set—or components of it—has to be inhibited to enable T1 response selection at short SOAs. At long SOAs, S2 might be presented after the response

for T1 has been selected, so that the stimulus-triggered activation of the T2 task set does not require inhibition. The PRP effect would then partly reflect the time needed to overcome the inhibitory aftermath of the T2 task set.

An alternative explanation might be negative priming. During T1 response selection in trials with short SOA, subjects are confronted with the target S1 for which a response has to be selected first and with the distractor S2 which, when assuming sequential response selection, has to be ignored until the T1 response selection is finished. The previously ignored S2, however, subsequently requires a response in T2, possibly resulting in negative priming which might measure besides other processes (e.g., episodic retrieval) inhibition at the level of individual stimulus representations (see D'Angelo et al., 2016, for a review; see also Hoffmann, Kiesel, & Sebald, 2003). In contrast to short SOAs, at long SOAs, S2 might appear at a point in time when it is not longer perceived as a distractor and thus would not be subject to negative priming. Hence, short SOAs would result in negative priming of S2, whereas long SOAs would not. It is also reasonable that not the S2 representation but the S2 onset location is subject to this negative priming effect.[5]

Although Study II did not allow us to further determine the cognitive control processes reflected by the correlation between the PRP effect and switch costs, Study II represents a first step towards understanding the underlying mechanisms of the PRP effect. The findings of Study II indicate for the first time that cognitive control might contribute to the PRP effect.

4.1.3 Embedding the findings into models of cognitive control in dual-tasking

The first research line on local task-set control indicates that dual-task processing depends, in addition to the mechanisms leading to the PRP effect, on shifting processes and possibly also on T1 response inhibition and/or episodic binding. Given sequential response selection, these processes occur after the response selection for T1 and before that for T2.

Shifting processes, conceptualized as task-set reconfiguration, are considered, in the modified RSB model endorsed by Lien and colleagues (2003) and the ECTVA model. The ECTVA model additionally refers to T1 response inhibition. In detail, before response selection starts for T2, T1 response counters are inhibited and a new parameter-level task set for T2 is transmitted to TVA. Since capacity sharing models and the EPIC architecture suggest that responses can be selected concurrently for T1 and T2, there is no obligatory task-set

[5] With intermediate SOAs, the detrimental effect of T2 task-set inhibition and negative priming on the T2 performance should be stronger than with long SOAs and weaker than with short SOAs. How this can be conceptualized in detail remains presently unclear, meaning that more research is needed in this regard.

reconfiguration stage for T2 postulated in these models. As regards T1 response inhibition, no explicit assumptions are made by RSB models, capacity sharing models, and the EPIC framework. Episodic binding is referred to in none of these models.

The first research line indicates not only that dual-task performance relies generally on cognitive control but also that the PRP effect itself might reflect cognitive control processes. In this context, besides rapid switching between two tasks and T2 task set inhibition, the negative priming of S2 representations and S2 onset locations which might possibly reflect inhibition has been discussed as potential sources of the PRP effect. These processes are conceptualized in none of the reviewed dual-task models.

It is noteworthy that the ECTVA model is the only account that explicitly refers to S2 onset locations. More precisely, parameter-level task sets contain, besides other parameters, π parameters which define the importance of selecting stimuli with certain characteristics, such as a specific onset location. However, the π parameters do not contribute to the PRP effect.[6]

From this short summary, it is evident that the reviewed dual-task models are unable to account for the complete pattern of results observed in the first line of research on local task-pair set control. Importantly, no model assumes the core components of cognitive control to contribute to the PRP effect.

4.2 Cognitive control at the global level of dual-tasking

The second research line addressed the question of whether the identity of T1 and T2 is represented jointly in a single mental representation, which is referred to as task-pair set, and if so, which selection mechanisms act at the global level of these task-pair sets. To study these questions, a novel empirical approach, termed task-pair switching logic, was developed and implemented into the PRP procedure. According to this logic, at least three tasks (e.g., A, B, and C) are combined to task-pairs in which T1 is constant and T2 varies across trials or vice versa (e.g., Task-Pair 1: C as T1 and A as T2 [CA]; Task-Pair 2: CB; or Task-Pair 1: AC; Task-Pair 2: BC). The sequence of the task-pairs is manipulated on a trial-by-trial basis, and a cue at

[6] To enable the π parameters to contribute to the PRP effect, π parameters in the parameter-level task set for T1 would, for example, have to differ in their values across SOAs and there would have to be proactive interference between the previous and the current parameters in TVA. The interference affects the values of the new parameters, resulting in a weighted average of the current and previous parameters (see Logan & Gordon, 2001, for a similar proposal to account for sequential task-switching performance). The π parameters for S2 in the T2 parameter-level task set would be lower when they have been set previously extremely low in the T1 parameter-level task set with short SOA compared to when they have been set less low with long SOA. Since the evidence accumulation processes takes longer with low than high parameter values, T2 performance would be, even with the same time required for T2 task set reconfiguration, worse with short than with long SOA.

the beginning of each trial indicates the task-pair to be performed. The variation of the task-pair sequence results in *n*-1 task-pair switch trials in which the task-pair in a given trial differs from that in the previous trials (e.g., Task-Pair 1 in trial *n*-1 and Task-Pair 2 in trial *n*) and in *n*-1 task-pair repetition trials in which the task-pair is the same as that performed in the previous trial (e.g., Task-Pair 2 in trial *n*-1 and in trial *n*).

The rationale of the following studies is that worse performance in *n*-1 task-pair switch trials than in *n*-1 task-pair repetition trials, referred to as *n*-1 task-pair switch costs, would provide evidence that information about subtask identity was activated in the previous trial and persisted to a certain degree until the next trial where it facilitates performance when the task-pair is repeated and hampers performance when the task-pair changes. Since T1 in a given trial always differs from T2 in the previous trial, this performance cost would not be attributable to task-set reconfiguration and/or task set inertia at the local level of switching from T2 in trial *n*-1 to T1 in trial *n*. Thus, *n*-1 task-pair switch costs would be an index of the shifting component of cognitive control at the global processing level of task-pair sets.

Since the majority of the reviewed models on dual tasks propose sequential response selection for T1 and T2, *n*-1 task-pair switch costs in T1 should be of particular interest to explore whether information about the subtask identity is activated during dual-tasking. The *n*-1 task-pair switch costs in T2, however, should be interpreted cautiously. This is because with each prolongation of T1 processing before or within the stage of response selection, T2 response selection is queued for the same time (see Strobach, Schütz, & Schubert, 2015, for a review on the importance of T1 performance). Consequently, *n*-1 task-pair switch costs can simply propagate from T1 to T2 and the performance cost in T2 would, thus, provide no conclusive evidence for the activation of subtask identity information in the preceding trial. Based on this reasoning, the following findings are reported with a special focus on T1.

4.2.1 Task-pair set as a joint mental representation of the identity of the individual tasks of a dual task

In ***Study III (Hirsch, Nolden, Philipp, & Koch, 2017)***, two experiments were conducted to investigate whether task-pair sets are activated during dual-task processing. In *Experiment 1*, T1 varied across task-pairs and T2 was held constant, whereas in *Experiment 2*, T1 was constant and T2 varied across task-pairs. In both experiments, there were substantial PRP effects and *n*-1 task-pair switch costs in T1 and T2. The *n*-1 task-pair switch cost in T2 was of comparable size across SOAs, which at the same time also means that the PRP effect did not differ depending on whether a task-pair changed or was repeated.

A major finding of this study is that *n*-1 task-pair switch costs in T1 also emerge when T1 is constant across task-pairs. With a varying T1 across task-pairs an alternative explanation for *n*-1 task-pair switch costs in T1 could be that, despite the intervening T2, the activation of T1 persists across trials. This activation would hamper T1 performance in *n*-1 task-pair switch trials where T1 differs from that performed in the previous trial and facilitate T1 performance in *n*-1 task-pair repetition trials where T1 is the same as that performed in the previous trial. *N*-1 task-pair switch costs in T1 would then have been rather due to repetition-priming effects of T1 across trials than due to switching task-pair sets per se. Thus, the *n*-1 task-pair switch cost with a constant T1 and a varying T2 provides strong evidence for the activation of task-pair sets containing information about the identity of the two subtasks to be performed in temporal overlap. This activation persists to a certain degree until the next trial, where it facilitates performance, when the task-pair is repeated and hampers performance when the task-pair changes. This indicates that T1 and T2 are cognitively represented as a more complex hierarchically higher single task and that the cognitive representation of a dual task includes, in addition to the task sets of T1 and T2, a task-pair set.

Moreover, we assumed that the task-pair set is an explicit representation (i.e., separate representation). Since subtask identity has to be available before the processing of the two subtasks, it is conceivable that task-pair sets are organized at a hierarchically higher-level than the subtask-specific task sets (see Cooper & Shallice, 2000; Humphreys & Forde, 1998, for a similar notion regarding multistep sequential tasks). In this sense, the hierarchy would be defined as a temporal precedence of information and/or processes related to task-pair set determination, followed by an activation of the subtask-specific task sets (i.e., hierarchical account; see Figure 4).

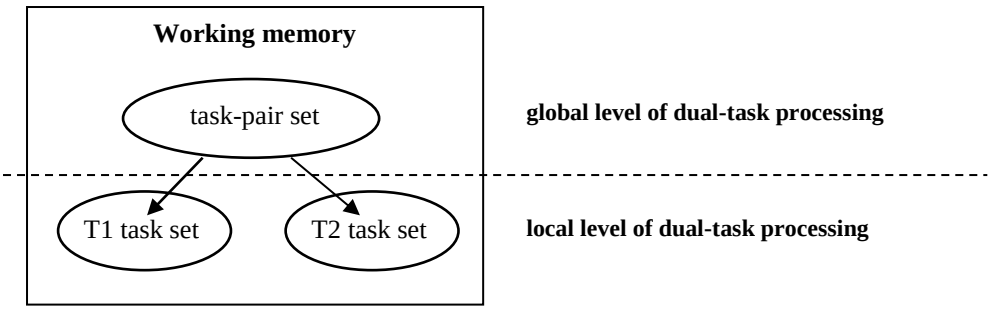

Figure 4. Visualization of a hierarchical multi-component mental representation of a dual task. T1 = Task 1; T2 = Task 2.

This hierarchical account, thus, implies a sequential activation of the task-pair set and the subtask-specific task sets. When the task-pair changes, time-consuming and error-prone

processes related to task-pair set reconfiguration and/or the resolution of proactive interference ensure the instantiation of the new task-pair set. The selection of the T1 task set needed for response selection in T1 is prolonged for the time required to activate a task-pair set in *n*-1 task-pair switch trials, resulting in *n*-1 task-pair switch costs in T1 (see Figure 5).

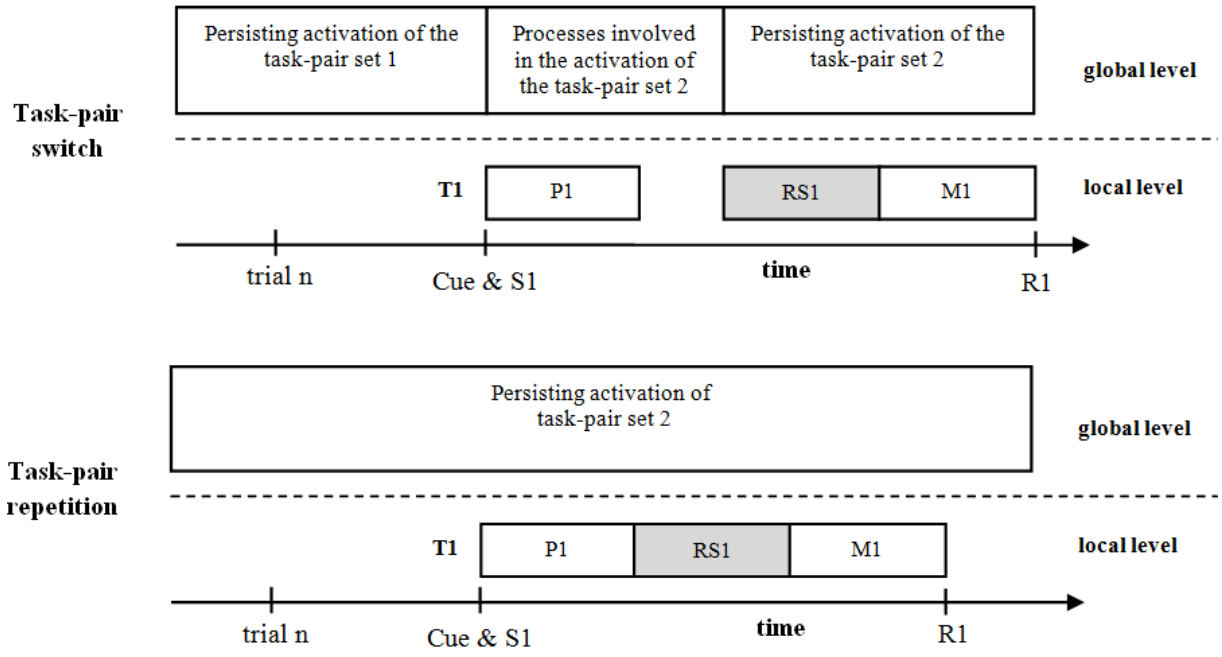

Figure 5. Visualization of the sequential activation of task-pair sets and subtask-specific task sets. P1 = perceptual processing stage for Task 1 (T1); RS1 = response-selection stage for T1; M1 = motor stage for T1. The time line between Stimulus 1 (S1) and Response 1 (R1) represents the reaction time for T1.

To explore when the task-pair set is available during dual-task processing, we re-analyzed the data of Study III with regard to the effect of the SOA sequence (switch vs. repetition) on the task-pair switching performance. When cues activate the appropriate task-pair sets before the subtask-specific task sets are selected, as predicted by the proposed hierarchical account, the SOA should be not part of a task-pair set. This is because the SOA is not specified by the cue and is thus unknown at this point in time. Alternatively, a task-pair set might be only available after performing a dual-task trial which would indicate that subjects adopted an episodic representation of the specific task-pair of the previous trial. In this case, the SOA should be part of the task-pair set and a non-hierarchical account (e.g., binding) could explain *n*-1 task-pair switch costs. In line with the hierarchical account, *n*-1 task-pair switch costs did not significantly differ across SOA repetitions and SOA switches. The findings of this

analysis represent a first indication for the hierarchical account.[7] However, future research should test this account more systematically.

In sum, it can be concluded that the mental task representation needed to perform a dual task consists of multiple components, including a task-pair set at a hierarchically higher level than the task sets for T1 and T2. Switching between task-pairs makes task-pair set reconfiguration and/or the resolution of proactive interference necessary, thereby queuing cognitive processes related to the activation of the T1 task set.

4.2.2 Selection mechanism at the global level of dual-tasking

To get a deeper insight into task-pair set control, ***Study IV (Hirsch, Nolden, & Koch, 2017)*** investigated whether inhibition is the selection mechanism at the global level of task-pair sets. It was hypothesized that to select one of two task-pair sets, the activation of the relevant task-pair set has to be increased, whereas the activation of the currently irrelevant task-pair set has to be inhibited. This hypothesis was tested based on the *n*-2 backward inhibition paradigm developed by Mayr and Keele (2000) in the general task-switching domain (see Koch et al., 2010, for a review on inhibition).

To implement this paradigm into the task-pair switching logic, four tasks were combined to three task-pairs. When inhibition is the selection mechanism at the global level of task-pair sets, performance should be worse in *n*-2 task-pair repetition trials (e.g., Task-Pair 1 → Task-Pair 2 → Task-Pair 1) than in *n*-2 task-pair switch trials (e.g., Task-Pair 3 → Task-Pair 2 → Task-Pair 1). This is because in *n*-2 task-pair repetition trials, subjects switch to a task-pair which was inhibited in trial *n*-1, whereas in *n*-2 task-pair switch trials, they switch to a task-pair that was not inhibited in trial *n*-1. Thus, there should be a stronger inhibitory aftermath in *n*-2 task-pair repetition trials than in *n*-1 task-pair switch trials, resulting in *n*-2 task-pair repetition costs.

The role of inhibition at the global level of task-pair set control was explored in three experiments. Experiment 1 and Experiment 2 included immediate (i.e., *n*-1) task-pair repetitions, allowing, besides the examination of *n*-2 task-pair repetition costs, the analysis of

[7] Note that there was a non-significant trend towards worse T2 performance in SOA repetitions than in SOA switches in Experiment 1 and towards larger *n*-1 task-pair switch costs in SOA switches compared to SOA repetitions in Experiment 2 (both *p*s = .07). Moreover, the SOA sequence was not systematically varied in Study III. However, a yet unpublished task-pair switching study with a constant T1 and a varying T2 provides additional evidence that task-pair sets are activated by cues (Hirsch, Nolden, & Koch, 2018). In Experiment 2 of this study, we found comparable *n*-1 task-pair switch costs after Go trials and NoGo trials. There was only a trend towards a preparatory reduction of *n*-1 task-pair switch costs. However, when defining the task-pair sequence based on the task-pair that was performed before a NoGo trial, no *n*-1 task-pair switch costs were observed. In Experiment 1 of this study, we used two cues per task-pair and found substantial *n*-1 task-pair switch costs even when the cue switched in both *n*-1 task-pair switch trials and *n*-1 task-pair repetition trials.

n-1 task-pair switch costs. The experiments differed in the degree of response-set overlap. In Experiment 1, responses overlapped conceptually, whereas in Experiment 2, they overlapped physically. In Experiment 3, responses overlapped conceptually like in Experiment 1, but no immediate task-pair repetitions were allowed. Immediate task-pair repetitions were not included because it has been shown that in the general task-switching domain immediate task repetitions reduce the effects of the *n*-2 task sequence (Philipp & Koch, 2006).

In Experiment 1 and Experiment 2, we observed, in addition to a PRP effect, *n*-1 task-pair switch cost in T1 and T2. We thus replicated the findings of Study III and extended them from switching between two task-pairs to more complex settings with three task-pairs. In contrast to Experiment 1 and to the experiments in Study III, in the present Experiment 2, *n*-1 task-pair switch costs in T2 were larger with short than long SOA, and at the same time, the PRP effect was larger in *n*-1 task-pair switch trials than in *n*-1 task-pair repetition trials.

Regarding the *n*-2 task-pair sequence, we found an *n*-2 task-pair repetition benefit across all three experiments (i.e., Experiment 1 and 2: in T1; Experiment 3: in T2). *N*-2 task-pair repetition benefits indicate that the activation of a task-pair set persists even after the execution of a dual task. When the task-pair is repeated, this persisting activation is beneficial because it positively primes the correct task-pair. When the task-pair changes, the persisting activation, however, is detrimental because it leads to interference between the previously and currently relevant task-pair set, thereby prolonging the implementation of the intended task-pair set.

The residual activation, and thus, also the priming should be stronger the more recently the task-pair set has been applied. In *n*-2 task-pair repetition trials, the relevant task-pair set has been employed two trials before, so that its activation should be more marked than that of the relevant task-pair set in *n*-2 task-pair switch trials where the relevant task-pair set was used more than two trials before. Based on this reasoning, performance in *n*-2 task-pair repetition trials should be improved compared to *n*-2 task-pair switch trials.

Since we used a varying T1 and a constant T2 in Study IV, T1 repetition priming effects across task-pairs might be an alternative explanation for the observed *n*-1 task-pair switch costs and *n*-2 task-pair repetition benefits. However, as indicated by the forward and backward R-R compatibility effects, there was interference between the T1 and T2 task sets at the response level. As in the general task-switching domain, between-task interference at the level of response sets has been shown to be resolved by inhibiting the previous task set (Gade & Koch, 2007), we assumed that the activation of the T1 task set was inhibited during T2 processing, and thus, did not persist across trials. The finding of R-R compatibility effects, along with the

n-1 task-pair switch costs observed with a constant T1 in Study III, suggests that T1 repetition priming effects were not the sole source of the observed effects.

To sum up, the findings suggest that persisting task-pair set activation which results in residual positive priming of the previously applied task-pair set is the crucial selection mechanism at the global level of task-pair sets (for a similar account in task switching, see Altmann & Gray, 2008). Whether the reviewed dual-task models can account for *n*-1 task-pair switch costs and *n*-2 task-pair repetition benefits will be discussed in the next section.

4.2.3 Embedding the findings into models of cognitive control in dual-tasking

The second research line on the global level of dual-task processing demonstrated two novel findings. Firstly, switching between task-pairs leads to *n*-1 task-pair switch costs, suggesting that the identity of T1 and T2 is represented jointly in a single task-pair set. Secondly, *n*-2 task-pair repetition benefits indicates that persisting task-pair set activation which results in residual positive priming of the previous task-pair set is the crucial selection mechanism at the global level of task-pair sets.

N-1 task-pair switch costs and *n*-2 task-pair repetition benefits cannot be accounted for by any of the introduced models. Nevertheless, the ECTVA model has potential to be extended to explain these performance costs.[8] It proposes the existence of an explicitly represented task-level task set, which is a propositional representation of task instructions. In line with our reasoning, this task-level task set is assumed to be organized hierarchically. The higher level determines the order in which T1 and T2 have to be performed, whereas the lower level defines each task separately. The consideration of a task-level task set, however, is not sufficient to account for *n*-1 task-pair switch costs because it solely refers to the subtask order which we did not manipulate in our studies (see Section 6.4 for a discussion).

Even if the ECTVA model implemented task-pair sets into the task-level task sets, it would not have the power to account for *n*-1 task-pair switch costs because the developers of the model did not make much use of the task-level task set during their model simulations. They were "more concerned with the interaction between working memory and TVA than with the fate of the propositional representation of the task set in working memory" (Logan & Gordon, 2001, p. 396). Therefore, in this model, reconfiguration processes refer only to the local level of T1 and T2. The implementation of a reconfiguration stage dedicated to task-level task sets

[8] Note that the ECTVA model refers to dual-task situations with two visual stimuli. In our task-pair switching studies, a visual and an auditory task were used, so that it remains open as to whether the proposed mechanisms in the ECTVA model are transferable to tasks which are based on other modalities.

would also not be sufficient to account for *n*-1 task-pair switch costs. Task-pair set reconfiguration is required in both *n*-2 task-pair switch trials and *n*-2 task-pair repetition trials but nevertheless T1 performance differs across these trial types.

To explain *n*-1 task-pair switch costs and *n*-2 task-pair repetition benefits, a trial-by-trial memory of task-pair sets is needed which allows for persisting task-pair set activation and interference between task-pair sets. Such trial-by-trial memory is presently not considered in the reviewed dual-task models.

5 Summary and theoretical implications of the present findings

Overall, four studies were conducted on the role of cognitive control in dual-tasking. In the following, a summary of the main findings and a presentation of the novel theoretical implications for cognitive control at the local level of task sets and the global level of task-pair sets is provided.

5.1 Local level of task-set control in dual-tasking

The studies conducted within the scope of the first line of research focused on cognitive control at the local level of the T1 and T2 task sets. An overview of the main findings and conclusions of this research line is given in Table 1.

Study I showed larger age-related differences in the preparatory reduction of alternation costs with overlapping than non-overlapping task sets. Note that alternation costs represent a mixture of mixing costs (i.e., marker of task-set maintaining and updating) and switch costs (i.e., marker of task-set shifting). Considering the age-sensitivity of mixing costs and the age-insensitivity of switch costs (e.g., Wasylyshyn et al., 2011), along with the age-related decline in the distractor interference resolution ability (e.g., Lustig & Jantz, 2015), this finding suggests that old adults suffer more than young adults from the activation of the irrelevant task set during proactively operating task-set maintaining and updating processes. Thus, the reliably observed age-related increase in mixing costs might be partly due to impaired preparatory processes involved in the updating and maintaining of interfering, and thus, simultaneously activated task sets in repetition trials in which no direct carry-over effects of the irrelevant task-set activation due to its prior application occur.

From the cognitive aging perspective, this is a major finding because the role of between-task interference on age-related differences in preparatory task-set updating and maintaining processes has so far received little attention. Regarding the focus of the present dissertation, this finding, along with forward and backward R-R compatibility effects (see also

Study IV), indicates that task sets or their components are activated to some extent simultaneously in task-switching and dual-task situations. The parallel task-set activation might provide a ground for common cognitive control processes.

Table 1.

Overview of the main findings and conclusions of the first line of research on the local level of dual-tasking.

Study	Main findings	Main conclusions
Study I (Hirsch, Schwarzkopp, Declerck, Reese, & Koch, 2016)		
Experiment 1	- Comparable preparatory reduction of alternation costs in old and young adults with non-overlapping stimulus sets	An age-related decline in the preparatory processes involved in maintaining and updating interfering, and thus, simultaneously activated task sets in WM contributes to increased mixing costs in old age
Experiment 2	- Smaller preparatory reduction of alternation costs in old adults as compared to young adults with overlapping stimulus sets	
	<u>Between-experiment comparison:</u> - Stronger age-related impairments in the preparatory reduction of alternation costs with overlapping than non-overlapping stimulus sets	Since in dual-task contexts task sets (or their components) are also activated simultaneously, parallel task-set activation is a common ground for related mechanisms of cognitive control in task-switching and dual-task situations
Study II (Hirsch, Nolden, Declerck, & Koch, in press)		
Switching part	- Switch costs	Shifting processes contribute to dual-task performance when different tasks are performed as T1 and T2
Dual-task part	- PRP effect	
	- Switch costs in T2 which were comparable in magnitude across SOAs	
	- Response-repetition benefit in T2 of T1-T2 repetition trials and response-repetition costs in T2 of T1-T2 switch trials which did not differ in their size across SOAs	T1 response inhibition and/or episodic binding might contribute to dual-task performance
	<u>Cross-paradigm correlation analysis:</u> - Correlations between switch costs in the task-switching part, switch costs in T2 of the dual-task part, and the PRP effect, irrespective of whether the PRP effect was calculated averaged over T1-T2 switch and repetition trials or whether the PRP effect was solely based on T1-T2 repetition trials	In addition to or instead of a structural or strategic response-selection bottleneck, the PRP effect reflects, at least partly, those cognitive control processes that are also measured by switching-related performance costs

Study II showed that dual-task performance relies on shifting processes, at least when different tasks are performed as T1 and T2 (cf. switch costs in T2 which were comparable in size across SOAs and correlation between switch costs in T2 and switch costs in the task-switching part), and on T1 response inhibition and/or episodic binding (cf. response-repetition effects in T2 which did not differ in their magnitude across SOAs). Given sequential response selection, these processes occur after response selection for T1 and before that for T2. Hence, these cognitive processes contribute to dual-task performance but act independently of the cognitive mechanisms that are reflected by the PRP effect.

Most importantly from both the empirical and the theoretical perspective, the PRP effect itself seems to reflect, at least partly, cognitive control processes that are related to those underlying switch costs. Switch costs are commonly interpreted as being attributable to the shifting and inhibition components of cognitive control. Hence, in addition to or instead of structural and strategic response-selection bottlenecks, the PRP effect might reflect, at least partly, the shifting and inhibition components of cognitive control (cf. correlations between the PRP effect in T1-T2 repetitions, switch costs in T2, and switch costs in the task-switching part). In this context, the rapid switching between the components of the T1 and T2 task sets, T2 task set inhibition, and negative priming of S2 representations and S2 onset locations have been proposed as potential sources of the PRP effect.

To the best of my knowledge, Study II is the first to provide an empirical basis for the theoretical implication that the shifting and inhibition components of cognitive control might contribute to the PRP effect. Taking into account that the extant dual-task models do not consider these components to contribute to the PRP effect, it can be argued that there is a residue in both empirical approaches and theorizing on dual-tasking.

Noteworthy, Miyake and colleagues (2000), who identified WM updating, inhibition, and shifting as the core components of cognitive control, found dual-task costs, measured as performance difference between dual-task conditions with a SOA of 0 ms and single-task conditions, to be not related to any of the core components of cognitive control. Therefore, they concluded that dual-task performance might rely on an independent component of cognitive control. However, they used continuous tasks and did not assess the PRP effect which might be the reason for the heterogeneous findings across their and our studies.

In older dual-task studies, the PRP effect has usually been interpreted as a result of structural limitations of the cognitive system, instead of relating it to cognitive control (see, e.g., Pashler, 1994, for a review). Only recently has more focus been placed on the role of cognitive control in dual-tasking. For instance, in training studies, the practice-induced

improvement of dual-task-related performance costs is accounted for by an optimization of dual-task coordination skills (e.g., Liepelt, Strobach, Frensch, & Schubert, 2011; Schubert, Liepelt, Kübler, & Strobach, 2017). Dual-task coordination is considered in this research domain as a separate component of cognitive control which is responsible for efficiently coordinating and scheduling two simultaneously ongoing task streams (see Strobach & Schubert, 2017, for a review). In the light of the findings of the present dissertation, it would be interesting to explore whether dual-task coordination is indeed dissociable from the shifting and inhibition components. Even though the relationship between dual-task coordination skills and the shifting and inhibition components has not yet been specified, the present dissertation, along with studies on dual-task training, strongly stresses a new theoretical view on the PRP effect; it is a view that considers the involvement of cognitive control processes (see also Schubert, 2008; Schubert & Szameitat, 2003).

5.2 Global level of task-pair set control in dual-tasking

The studies conducted in the second line of research focused on cognitive control at the global level of task-pair sets. An overview of the main findings and main conclusions of this line of research is provided in Table 2. The *n*-1 task-pair switch costs observed in Study III and IV indicate that information about the identity of T1 and T2 is jointly represented in a single task-pair set. This suggests that the mental representation needed to perform a dual task consists of multiple components comprising a task-pair set and the task sets for T1 and T2.

We assumed that task-pair sets are explicitly represented. Since the subtask identity has to be available before the subtasks are selected, task-pair sets should be organized at a hierarchically higher-level than the subtask-specific task sets. The hierarchy is thus defined as a temporal precedence of information and processes related to subtask identity determination (i.e., task-pair sets), followed by an activation of the T1 and T2 task sets. A first empirical indication for this hierarchical account was found based on a re-analysis of Study III. The re-analysis showed that the SOA sequence does not affect task-pair switching performance, indicating that the SOA is not part of a task-pair set. This, in turn, suggests that task-pair sets are activated by cues. Since cues provide no information about the SOA, the SOA is not part of a task-pair set. However, the hierarchical account should be tested more systematically.

N-2 task-pair repetition benefits in Study IV indicate that persisting task-pair set activation which results in residual positive priming of the previously used task-pair set is the crucial selection mechanism at the global level of task-pair sets. More precisely, task-pair set activation persists even after the execution of a dual task. The persisting activation of a

previously used task-pair set positively primes the implementation of the intended task-pair set when a task-pair is repeated, and it hampers the instantiation of a task-pair set when the task-pair changes. Processes related to the activation of the T1 task set are therefore queued when there is a task-pair switch, resulting in *n*-1 task-pair switch costs.

Table 2.

Overview of the main findings and conclusions of the second research line on the global level of dual-tasking.

Study	Main findings	Main conclusions
Study III (Hirsch, Nolden, Philipp, & Koch, 2017)		
Experiment 1	- *N*-1 task-pair switch costs with a varying T1 and a constant T2	Task-pair sets are activated during dual-tasking
Experiment 2	- *N*-1 task-pair switch costs with a constant T1 and a varying T2	T1 repetition priming effects are not an alternative explanation for *n*-1 task-pair switch costs
	<u>Re-analysis</u> - No effect of SOA sequence on *n*-1 task-pair switch costs in Experiment 1 and Experiment 2	Task-pair sets are explicitly represented and can be activated by cues (i.e., hierarchical account)
Study IV (Hirsch, Nolden, & Koch, 2017)		
Task-pair switching logic with a varying T1 and a constant T2		
Experiment 1	- *N*-1 task-pair switch costs - *N*-2 task-pair repetition benefit	
Experiment 2	- *N*-1 task-pair switch costs - Increased *n*-1 task-pair switch costs in T2 with short compared to long SOA and an increased PRP effect in *n*-1 task-pair switch trials compared to *n*-1 task-pair repetition trials - *N*-2 task-pair repetition benefit	Persisting task-pair set activation which results in residual positive priming of the previously used task-pair set is the crucial selection mechanism at the global level of task-pair sets
Experiment 3	- *N*-2 task-pair repetition benefit	

Research and models on dual-tasking have not yet considered that dual-tasking requires the selection of a task-pair set, and that switching between such task-pair sets might be required during dual-tasking. This dissertation showed this for the first time, thereby providing both a new empirical approach to study the mechanisms of cognitive control acting at the global level of dual-task processing and novel theoretical implications. To account for the findings on the

global task-pair level, a dual-task model is needed that conceptualizes a trial-by-trial memory of task-pairs and allows for interference in this memory.

Note that the findings of the second research line expand the literature on dual-tasking by demonstrating that at the global level of dual-task processing not only the order of the subtasks but also their identity has to be specified. Empirical evidence for order control in dual tasks comes from numerous PRP studies (e.g., De Jong, 1995; Kübler & Schubert, 2017; Luria & Meiran, 2003, 2006; Szameitat, Schubert, Müller, & von Cramon, 2002; see Schubert, 2008, for a review). These studies showed that changes in the order of T1 and T2 (e.g., A as T1 and B as T2 in trial *n*-1 and B as T1 and A as T2 in trial *n*) lead to a performance cost, referred to as *n*-1 order switch cost (i.e., worse performance in *n*-1 order switch trials than in *n*-1 order repetition trials; e.g., Kübler, Reimer, Strobach, & Schubert, 2018; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006). Moreover, the studies demonstrated that performing dual tasks in the context of a varying T1-T2 order results in worse performance than performing dual tasks in contexts where only one T1-T2 order is relevant. These performance impairments have been shown to occur even if a T1-T2 order which is presented intermixed with another T1-T2 order is repeated across two dual tasks (i.e., order mixing costs: worse performance in *n*-1 order repetition trials than in single-order blocks; Luria & Meiran, 2003; Strobach, Soutschek, Antonenko, Flöel, & Schubert, 2015).

Based on these findings, it has been concluded that task order is explicitly represented in the cognitive system (e.g., Luria & Meiran, 2003; Szameitat et al., 2002, 2006). In line with the proposed theoretical underpinnings of *n*-1 task-pair switch costs, *n*-1 order switch costs have been interpreted as an index of priming-related and transient memory-based mechanisms of cognitive control that ensure mental adaptations to the relevant task order on a trial-by-trial level (e.g., Kübler et al., 2018). Order mixing costs, in contrast, are assumed to measure sustained control reflected by cognitive processes dedicated to the monitoring and updating of incoming information regarding subtask order changes in WM (e.g., Kübler et al., 2018). The present dissertation, along with dual-task studies on order control, provides strong evidence that cognitive control in dual-tasking is not restricted to the T1 and T2 task sets.

5.3 The interplay between local task-set control and global task-pair set control

The present dissertation showed that dual-tasking relies on both task-set control and task-pair set control. A next step towards obtaining a more complete picture of the cognitive control mechanisms underlying dual-task performance is the integration of these research lines.

In the present studies, there was an interplay between the local level of task-set control and the global level of task-pair set control in only one of the five experiments. More specifically, *n*-1 task-pair switch costs in T2 were more pronounced in trials with a short than a long SOA. At the same time, the PRP effect was more marked in *n*-1 task-pair switch than in *n*-1 task-pair repetition trials. Importantly, this overadditive interaction between SOA and *n*-1 task-pair sequence was not significant in T1. Thus, the data pattern was specific to T2.

An explanation for smaller *n*-1 task-pair switch costs in T2 with long than short SOA might be that *n*-1 task-pair switch costs in T2 are the result of a propagation effect which is absorbed with long SOA. More precisely, with short SOA, the perceptual processing for T1 and T2 starts and ends almost at the same time, so that response selection is required simultaneously for both tasks. In *n*-1 task-pair switch trials where response selection for T1 is queued T2 response selection has to wait longer for the availability of the response-selection stage than in *n*-1 task-pair repetition trials, resulting in large *n*-1 task-pair switch costs with short SOA. With long SOAs, T2 perceptual processes occur during the waiting period for the availability of the response-selection stage, resulting in decreased *n*-1 task-pair switch costs.

This interaction was found in Experiment 2 of Study IV, which was the only one with physical response set overlap. With conceptually overlapping response sets, the interaction was not significant. Thus, the degree to which the T1 and T2 task sets overlap might affect the interplay between the two processing levels. To determine the underlying mechanisms of this interplay and the experimental conditions that lead to this interplay, further research is needed.

6 Open Issues

The primary theoretical contribution of the present dissertation is that dual-tasking relies on both local task-set control and global task-pair set control. This raises new questions regarding the underlying mechanisms of cognitive control in dual-task processing. Some of these questions will be described subsequently.

6.1 Inhibition at the local level of dual-tasking

Since the present dissertation shows that cognitive control contributes to the PRP effect, future research should strengthen the focus on its underlying cognitive mechanisms. In the general task-switching domain, an extended research line addressed inhibitory mechanisms of task-set control (see, e.g., Koch et al., 2010, for a review; Schneider & Logan, 2005). By contrast, in dual-task research, they have received little attention.

Inhibition at the local level of task sets can refer to both T1 and T2. On the one hand, it is conceivable that the T2 task set or its components are inhibited during T1 response selection. This inhibition can refer to the T2 in a given trial and to T2 preformed in the previous trial. On the other hand, it is also conceivable that inhibition is dedicated to T1 during T2 response selection. To advance theorizing in dual-tasking, an empirical approach that allows for studying inhibitory processes at the level of T1 and T2 task sets has to be developed. Ideally, this approach should offer the possibility to examine what exactly is inhibited during dual-tasking (e.g., S-R mappings, the mental representation of stimuli and responses), and how the inhibition mechanism works.

6.2 Dynamics of task-pair set activation at the global level of dual-tasking

For an extended understanding of the cognitive mechanisms underlying task-pair set control, it is of particular relevance to determine the dynamics of task-pair set activation. The *n*-2 task-pair repetition benefit observed in Study IV suggests persisting task-pair set activation which results in residual positive priming of task-pair sets as crucial selection mechanism at the level of task-pair sets. In the task-switching domain, Grange, Juvina, and Houghton (2013) concluded from computational modelling on task inhibition that the existence of *n*-2 task repetition benefits is an indicator that no inhibition occurs during task switching. When inhibition does not contribute to task-pair set selection, the question emerges whether task-pair set activation passively decays over time. Otherwise, whenever the task-pair changes, the cognitive system would have to ensure that the current task-pair set reaches an activation that is higher than the persisting activation of the previous task-pair set, resulting in "a catastrophic build up of proactive interference" (Altmann & Gray, 2008, p. 605).

In this context, a further important question is whether task-pair switches can be prepared in advance and thus whether processes involved in the activation of task-pair sets can act prior to the onset of the task stimuli. Smaller *n*-1 task-pair switch costs with long than short preparation time would suggest the involvement of proactive control processes that are responsible for bringing the cognitive system to a state of readiness to repeat or switch a task-pair. Residual *n*-1 task-pair switch costs would indicate that reactive control processes are recruited to overcome some additional interference when the task-pair is presented.

Moreover, it would be informative to further examine the interplay between the local level of task-set control and the global level of task-pair set control. This research is of particular importance because it can reveal whether task-pair set activation is solely based on cues or whether task-pair set activation can also arise from the S1 and S2 onsets. The present task-pair

switching studies did not allow us to further specify the interplay between the local level of task sets and the global level of task-pair sets so that the interplay and its underlying mechanisms remain an important topic for future research.

6.3 Working memory updating at the global level of dual-tasking

The research line on task-pair set control has so far focused on *n*-1 task-pair switch costs which are assumed to reflect transient cognitive control mechanisms that enable the shifting between task-pairs and thus ensure fast adaptations to the relevant task-pair from trial to trial. To elaborate the understanding of the underlying cognitive mechanisms of dual-task performance, it should be examined whether sustained components of cognitive control dedicated to the monitoring and updating of incoming information in WM with the aim of identifying task-pair switches are involved in task-pair set control. Considering that task-switching studies have showed the WM updating component to be impaired with old age and the shifting component to be intact, empirical evidence for the notion that *n*-1 task-pair switch costs and task-pair mixing costs reflect distinct cognitive control mechanisms can be obtained from age-related dissociations between these performance costs.

6.4 Order information at the global level of dual-tasking

The organization of the proposed hierarchical multi-component mental representation of a dual task has to be further specified. Aside from the question of how the T1 and T2 task sets are organized within this representation (i.e., flat, hierarchical, or componential organization; see, e.g., Philipp & Koch, 2010), it remains to be answered as to how task-pair sets and order-sets differ. On the one hand, it can be argued that in studies on order control, solely one task-pair set is needed. This is because the task-pair set, in its current definition, does not entail information about the processing order of the subtasks. Hence, which of the subtasks specified in a task-pair set is performed as T1 and which as T2 do not change the task-pair set. *N*-1 order switch costs, therefore, reflect performance costs occurring even though there is the same task-pair set relevant in both *n*-1 order switch trials and *n*-1 order repetition trials. This might be an indication that the subtask order is not controlled based on task-pair sets.

Taking into account that an order set is defined as an ordered list of the subtasks to be performed in a dual task (e.g., Luria & Meiran, 2003) and thus also entails information about the identity of the subtasks, it can also be argued that, in *n*-1 task-pair switch trials, the previous order-set cannot be used again even though one of the subtasks retains its position in the ordered

list. This is because an *n*-1 task-pair switch is unavoidably accompanied by the involvement of a subtask that was not considered in the previous task-pair set.

Thus, an *n*-1 task-pair repetition is always an *n*-1 order repetition and an *n*-1 task-pair switch is always an *n*-1 order switch, or at least a partial *n*-1 order switch. Considering this fact coupled with the possibility that it might be redundant to represent the same information at two different levels of a mental representation, it is conceivable that task-pair sets and order sets refer to the same mental representation, and that task-pair sets have to be expanded to include order information.

In this respect, a further essential step towards a better understanding of the underlying mechanisms of cognitive control at the global level of dual-tasking is to disentangle the effects of order-switching from those of task-pair switching, which is a challenging task. Given that the presented task-pair switching studies included no subtask order manipulation, a first way forward could be to examine if *n*-1 task-pair switch costs differ depending on whether a subtask switches or whether the same subtask is performed in a different order. However, since task-pair sequence and order sequence cannot be varied independently of each, the findings should be interpreted cautiously.

7 Conclusion

At the outset of this dissertation, an influential notion proposed by Pashler (2000) was introduced as the starting point of the presented research. He stated that switching-related performance costs are attributable to cognitive control, whereas the PRP effect is not. The empirical findings of the present dissertation contradict this reasoning. The findings indicate that the PRP effect reflects, in addition to or instead of a structural or strategic response-selection bottleneck, cognitive control processes that are related to those underlying switching-related performance costs. Moreover, the present dissertation showed that in addition to cognitive control mechanisms coordinating simultaneous task processing at the level of subtasks, successful dual-task performance is enabled by cognitive control mechanisms acting at the global level of hierarchical higher-level tasks (i.e., task-pairs). Thus, Pashler's idea that passive queuing of T2 response selection is the sole source of the PRP effect and that dual-task processing is restricted to the local level of the T1 and T2 task sets has to be revised. Overall, it can be concluded that there are multiple requirements on cognitive control in dual-tasking like it is stated in the title of the present dissertation.

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Study III

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Study IV

Hirsch, P., Nolden, S., & Koch, I. (2017). Higher-order cognitive control in dual tasks: Evidence from task-pair switching. *Journal of Experimental Psychology: Human Perception and Performance, 43*, 569-580. doi: 10.1037/xhp0000309

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Age-related differences in task switching and task preparation: Exploring the role of task-set competition

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Abstract

The present study focused on the role of task preparation in age-related task-switching deficits. In Experiment 1, we assessed the preparatory reduction of alternation costs (i.e., alternating-task conditions vs. single-task conditions) in twenty-two older adults (65-78 years) and 22 young adults (20-28 years) by varying the response-stimulus interval (RSI) in a task-switching paradigm with a predictable task sequence and univalent stimuli. In Experiment 2, in which new groups of 22 older adults (65-78 years) and 22 young adults (18-24 years) took part, we replicated Experiment 1 with bivalent stimuli, which were associated with both tasks and thus increased task-set competition. Whereas in Experiment 1, in which we used univalent stimuli, there were no age-related differences in the preparatory reduction of alternation costs, the data showed impaired task preparation in old age with bivalent stimuli in Experiment 2. These data support the notion that task-preparation deficits in old age occur particularly in situations of increased task-set competition.

(160 words)

Keywords: age-related task-switching deficits, task preparation, task-set competition

Introduction

Aging is accompanied by a decrease in cognitive control (see, e.g., Craik & Salthouse, 2000, for a review), which is defined as the ability to flexibly adjust goal-directed behaviour to constantly changing situational demands (Miller & Cohen, 2001). Age-related deficits in cognitive control have often been explored in studies requiring task switching (see, e.g., Wasylyshyn, Verhaeghen, & Sliwinski, 2011, for a meta-analysis). In these studies, older adults typically show larger performance costs when they are required to switch between tasks than young adults.

Switching-related performance costs are usually reduced when there is sufficient time available to prepare for a task switch (see, e.g., Kiesel et al., 2010, for a general review on task switching). Some studies provide evidence that older adults are able to prepare for a task switch at least as effectively as young adults (e.g., Hartley, Kieley, & Slabach, 1990; Kramer, Hahn, & Gopher, 1999, Experiment 2; Lawo & Koch, 2012). However, other studies observed an impaired task preparation in old age (e.g., Hsieh & Wu, 2010; Kramer et al., 1999, Experiment 3; Lawo, Philipp, Schuch, & Koch, 2012). Thus, studies about the effect of age on task preparation revealed mixed findings.

In the present study, we re-examined the effect of age on task preparation. In Experiment 1, we assessed switching-related performance costs and age-associated differences in the preparatory reduction of these costs using univalent stimuli. In Experiment 2, we explored whether such age-related differences are exacerbated when task-set competition is increased by using bivalent stimuli.

Task switching and accounts of switching-related performance costs

In the task-switching paradigm, subjects switch between two tasks or repeat them across trials. Performance is typically slower and more error prone in task switches than in repetitions (see, e.g., Kiesel et al., 2010, for a review). Depending on the experimental design, a distinction is drawn between three measures reflecting the increased cognitive demands in switch trials.

One of these measures is the *alternation cost*. This cost is computed by contrasting performance in single-task blocks, which are by definition repetition trials, with performance in alternating-task blocks, in which the task changes after each trial, and thus, no immediate task repetitions occur (e.g., Jersild, 1927).

Using mixed-task blocks where, in addition to switch trials, repetition trials are also included, *mixing costs* can be analyzed as a further index of performance deterioration. These costs are computed as the difference between the performance in repetition trials of mixed-task blocks and the performance in single-task blocks (e.g., Rubin & Meiran, 2005).

Finally, *switch costs* can be assessed as a third measure of performance degradation. These costs are calculated in mixed-task blocks by contrasting performance in repetition trials with that in switch trials (e.g., Rogers & Monsell, 1995).

Switching-related performance costs have been shown to be reduced when there is sufficient time available to prepare for the upcoming task (see, e.g., Kiesel et al., 2010, for a general review on task switching). Preparatory processes in task switching can be investigated by varying the cue-stimulus interval (CSI) in unpredictable task sequences (e.g., Meiran, 1996) or the response-stimulus interval (RSI) in predictable task sequences (e.g., Rogers & Monsell, 1995).

Different accounts have been proposed to explain the performance deterioration in switch trials and the reduction of this deterioration with preparation time. According to the proactive interference (PI) account by Allport, Styles, and Hsieh (1994), performance in switch trials is impaired because the target task set was irrelevant in the previous trial and therefore inhibited, whereas the non-target task set was relevant and received additional activation. In switch trials, this causes interference "in the form of continued priming of the previous task (competitor priming) and suppression (negative priming) of the currently intended task" (Allport et al., 1994, p. 293). Switching-related performance costs are reduced with preparation time because with long intervals, there is more time available for task-set dissipation than with short intervals, resulting in less interference in switch trials.

In contrast to the PI account, reconfiguration models assume that in switch trials, a task-set reconfiguration takes place which results in an increased activation of the relevant task set in working memory (e.g., Meiran, 2000; Rogers & Monsell, 1995). These reconfiguration processes are time-consuming, leading to slower responses in switch trials than in repetition trials. With long intervals, there is more time available for these reconfiguration processes than with short intervals, resulting in reduced switching-related performance costs.

Accounts of cognitive aging and the effect of age on task-switching performance

Numerous studies have addressed the question of whether there are age-related decreases in task-switching performance and of whether these decreases are the result of general limitations in the processing speed or of process-specific limitations. According to accounts of general processing limitations (e.g., general slowing hypothesis; Salthouse, 1996), the older adult's poorer performance in different tasks is due to a general decrease in processing speed in all cognitive processes. The reason for this decline may lie in an age-related reduction in the efficiency with which neurons transfer information (Cerella, 1985).

In contrast to accounts of general limitations in the processing speed, accounts of process-specific limitations assume that there are age-related impairments only in some cognitive processes and that these impairments are not a result of a decrease in processing speed (e.g., inhibitory deficit theory; Hasher & Zacks, 1988; Lustig, Hasher, & Zacks, 2007). Hence, to demonstrate such specific changes in cognitive processing, one needs to show that these changes cannot be explained by proportional slowing (see, e.g., Kray, 2006).

Research on the effect of age on task-switching abilities showed that there are age-related deficits in mixing costs (e.g., Reimers & Maylor, 2005; Verhaeghen & Cerella, 2002; Wasylyshyn et al., 2011), whereas age-related differences in switch costs are frequently non-existent (e.g., Hartley et al., 1990; Wasylyshyn et al., 2011) or only moderate (e.g., Kray & Lindenberger, 2000). The age-associated increase in mixing costs has been shown to be disproportional to the older adults' baseline performance (e.g., Kray, 2006), suggesting a process-specific account.

Mixing costs supposedly index cognitive processes of updating and maintaining two task sets in working memory (Mayr, 2001). Thus, these findings suggest that older adults' performance in task switching is hampered by a decline in these processes than by the requirement to switch between tasks. Alternation costs include additional costs due to flexible switching requirements, but these costs seem to be not age specific (see, e.g., Wasylyshyn et al., 2011, for a meta-analysis). Hence, the mechanisms leading to age-related differences in alternation costs should be the same as those reflected by mixing costs.

Mayr (2001) demonstrated that age-associated differences in switching-related performance costs are large when task-set competition is increased and the internal differentiation between task sets is difficult. For example, task-set competition is increased when stimuli and/or responses are bivalent. In contrast to univalent stimuli, which are linked to one task only, bivalent stimuli are associated with two tasks, resulting in competing task sets and in an increased difficulty of task set differentiation. When the responses for two tasks are separated, hence with no overlap between the response specifications of the tasks, the responses are univalent and the competition between the response sets is low. In contrast, the response set-up is bivalent and task-set competition is increased when responses for two tasks overlap physically (i.e., same set of response keys) or conceptually (i.e., two tasks are mapped onto different hands, but the same spatial mapping is used in both tasks). When stimuli and/or responses are bivalent, the maintenance and updating of task sets in working memory is particularly difficult because there is a high competition and interference between them. Thus,

univalent and bivalent stimuli as well as responses differ in the recruitment of working memory processes.

In addition to studies which explored whether older adults show larger switching-related performance costs than young adults, there are also studies that focused especially on age-associated differences in the preparatory reduction of switching-related performance costs. Several studies suggested intact task-preparation ability in old age comparable to that in young adults (e.g., Hartley et al., 1990; Lawo & Koch, 2012; Meiran, Gotler, & Perlman, 2001). However, some studies showed an age-related decrease in the preparatory efficiency (e.g., Hsieh & Wu, 2010; Kramer et al., 1999, Experiment 3; Lawo et al., 2012). Lawo et al. (2012), who found an age-related deficit in the preparatory reduction of alternation costs, argued that this deficit indicates that preparation processes involved in the updating of task sets in working memory are impaired in old age.

A reason for the inconsistent data pattern may lie in vast methodological differences between these studies. Apart from the stimuli and tasks, these differences concern, for example, the number of tasks (two vs. three), the type of the preparation interval (RSI vs. CSI), its duration, and the way of its variation (within blocks vs. across blocks).

Yet, in spite of these differences, a comparison of the existing studies suggests that older adults show impaired preparatory efficiency especially in situations with increased task-set competition, which hampers the maintenance and updating of task sets in working memory and hence increases the demands on working memory processing. In the study by Lawo et al. (2012), task-set competition was more pronounced than in the above reviewed studies because, in addition to bivalent stimuli, Lawo et al. (2012) used three tasks and subjects were required to differentiate between three instead of two competing task sets. This study suggests that age-related preparatory deficits in the context of increased task-set competition might contribute to age-related effects in switching-associated performance costs. Consequently, it is important to explore task-set competition, switching-related performance costs in old age, and age-related differences in preparation effects together. Since Mayr (2001) did not explore age-related differences in preparatory processes and the above reviewed studies about task preparation in old age used exclusively bivalent stimuli, there is currently little clarity on the impact of task-set competition on age-associated differences in preparatory processes.

The present study

In the present study, we investigated whether task-set competition contributes to age-related deficits in task switching and task preparation by varying the RSI and comparing task switching performance with univalent stimuli (Experiment 1) to that with bivalent stimuli

(Experiment 2). The goal was to replicate the finding of increased switching-related performance costs in old age in situations with high task-set competition (Mayr, 2001) and to extend the negative effect of task-set competition to task-preparation effects in old age. This would indicate that age-related differences in task preparation are increased particularly when working memory demands are high.

In the study by Lawo et al. (2012), which suggested age-related preparatory deficits, the task changed after each trial and hence task preparation was explored using alternating-task blocks. Since subjects have to switch back and forward in such blocks, alternation costs instigate strong competition and thus might be a more sensitive measure for age-related deficits in task preparation than mixing costs and switch costs. For this reason, we explored age-related differences in the preparatory efficiency based on alternation costs.

To assess the preparatory efficiency, we chose RSIs of 100 ms and 600 ms as preparation intervals. For predictable task sequences, Rogers and Monsell (1995) showed that RSIs up to 600 ms are used for the active preparation of a task switch and that there is no evidence for passive decay of the prepared task sets with RSIs of this length. Moreover, they demonstrated that for longer preparation intervals, there is no further preparatory reduction of switching-related performance costs, indicating that preparatory processes in predictable task sequences may take about 600 ms to accomplish.

Experiment 1

In Experiment 1, we aimed to examine age-related differences in the preparatory efficiency under situations of low task-set competition in a task-switching paradigm with a varying RSI and a predictable task sequence including a task switch after each trial. In contrast to most previous studies, we used univalent stimuli to reduce task-set competition by decreasing the interference between potential relevant task sets at the stimulus level.

We hypothesized that performance is slower and more error prone in alternating-task blocks than in single-task blocks, resulting in alternation costs and that the long RSI is used for task-set updating, leading to a reduction of these costs. Since due to the use of univalent stimuli, task-set competition and demands on working memory were low in Experiment 1, we examined whether there are still age-related effects in alternation costs and in task-preparation effects under these conditions.

Method

Participants. Twenty-two young adults (11 women; range: 20-28 years; *M* = 22.5) and 22 older adults (11 women; range: 65-78 years; *M* = 70.9) participated in the experiment.[1] The subjects were recruited from the participant pool of the Institute of Psychology of the RWTH

Aachen University and they were paid for their participation (10€) or received course credit. All subjects gave written consent to take part in the study after the experiment had been fully explained and they filled in a demographic questionnaire (see Table 1). The age groups did not significantly differ with regard to the number of years of formal education (young adults: 15.3 years; older adults: 15.5 years; two-tailed *t*-test: $t(42) = 0.25$, $p = .80$). All subjects had normal or corrected-to-normal vision and none of them reported suffering from neurological diseases.

----Table 1----

To ensure that there were no subjects with cognitive impairments, the subjects performed the screening instrument DemTec (Kessler, Calabrese, Kalbe, & Berger, 2000). The scores were comparable across groups (young adults: 17.6; older adults: 17.3; two tailed *t*-test: $t(42) = 1.52$, $p = .51$) and they were all below the cut-off indicative for mild cognitive impairment (MCI) or dementia.

Stimuli, tasks, and responses. The stimuli consisted of a fixation cross (+), digits (1 to 9, without 5), and capital letters (consonants: G, K, M, R; vowels: A, E, I, U).[2] The fixation cross was presented at screen center, where it stayed the entire experiment. Digits and letters were 2.0 cm in height and 1.6 cm in width, and were displayed in white Arial font on a black 17-inch screen placed at a distance of approximately 50 cm. Digits appeared to the left of the fixation cross and letters to the right of the fixation cross, or vice versa, counterbalanced across subjects. The distance from the stimuli to the fixation cross was 7.5 cm.

The tasks were to categorize digits as odd or even and to categorize letters as consonant or vowel, emphasizing speed and accuracy. These tasks were performed using the index and middle finger of the hand corresponding to the stimulus presentation location. We used the keys W, E, O, and P of a keyboard as response keys. The leftmost response of each hand was used either for the even or the consonant classification and the rightmost response for the odd or vowel classification. A reminder of key assignment was placed at the bottom of the screen.

Procedure. The experiment was run with E-Prime 1.1 (Psychology Software Tools, Inc. Pittsburgh, PA) in a single session with one subject at a time and started with one single-task block of 41 trials for each task type, followed by two alternating-task blocks, each consisting of 81 trials. After this, one single-task block of 41 trials was once again performed for each task. Prior to each single-task block, 5 practice trials were administered when the digit and the letter tasks were performed for the first time. The first alternating-task block was preceded by 8 practice trials.

In each single-task block, one of the two tasks was performed repeatedly. The stimuli were presented on one side of the screen and disappeared immediately after a response was executed. The next character occurred after a random RSI of 100 ms or 600 ms.

In alternating-task blocks, participants performed both tasks in alternating order. Hence, there was a fixed task sequence with a task switch after each trial. The stimuli were displayed alternately to the left and right of the fixation cross and disappeared directly after response execution. The RSI varied like in single-task blocks. One of the two alternating-task blocks started with the digit task and the other with the letter task.

The stimuli were presented randomly with the stipulation that no character was repeated in two consecutive trials and that all stimuli appeared equally often. Whether the subjects initially performed the digit or the letter task was counterbalanced across participants. The RSI varied randomly with the stipulation that there was the same number of short and long RSIs in each block.[3] Thus, there was the same number of trials with a short RSI and a long RSI across single-task blocks and alternating-task blocks. There was no time limit for responding and no error feedback.

Design. The 2 × 2 × 2 mixed design included the independent within-subjects variables task transition (switch trials vs. repetition trials) and RSI (100 ms vs. 600 ms). Age group (young vs. older adults) was a between-subjects variable. The dependent variables were RT and error rates.

Results and discussion

Practice trials, the first trial in each block, error trials, and trials following an error were excluded from reaction time (RT) analysis. Moreover, trials with RTs exceeding 3 *SD* from each individual's mean RT (per condition) were discarded as outliers (1.8% for each age group). Separate analyses of variance (ANOVAs) were run on mean RTs (see Figure 1) and error rates (see Table 2).

Since the use of mean RTs for a performance comparison of young and older adults is linked to the problem of age-related differences in baseline performance, we employed a logarithmic transformation that rescaled RTs of both age groups to a common scale, making them less susceptible to differences in overall speed (e.g., Kray & Lindenberger, 2000). Significant effects in log RTs indicate that age-related performance differences are disproportional to age-associated differences in the baseline performance (Faust, Balota, Spieler, & Ferraro, 1999). Thus, log RTs take general slowing into account (Salthouse, 1985). To confirm the results concerning significant effects of age groups on mean RT data, we repeated the analysis with log RTs.

---- Figure 1 and Table 2----

The ANOVA on RTs showed a main effect of task transition, $F(1, 42) = 66.75$, $p < .001$, $\eta_p^2 = .61$, indicating alternation costs of 164 ms (switch trials: 819 ms; repetition trials: 655 ms). Furthermore, the main effect of RSI was reliable, $F(1, 42) = 107.17$, $p < .001$, $\eta_p^2 = .72$. Responses were slower after a short RSI than a long RSI (775 ms vs. 700 ms), reflecting an RSI effect of 75 ms. The interaction of task transition and RSI was also significant, $F(1, 42) = 8.14$, $p < .01$, $\eta_p^2 = .16$, resulting in reduced alternation costs with long RSI (179 ms vs. 148 ms).

Moreover, there was a main effect of age group, $F(1, 42) = 44.93$, $p < .001$, $\eta_p^2 = .52$, reflecting longer RTs in older than in young adults (859 ms vs. 616 ms). Even though there was a clear numerical trend toward larger alternation costs in older than in young adults (202 ms vs. 125 ms), the interaction of task transition and age group was not significant, $F(1, 42) = 3.68$, $p = .06$, $\eta_p^2 = .08$. The interaction of age group and RSI was reliable, $F(1, 42) = 11.01$, $p < .01$, $\eta_p^2 = .21$, indicating that older adults showed a larger RSI effect than young adults (99 ms vs. 51 ms). However, the three-way interaction of task transition, RSI, and age group was not significant, $F(1, 42) = 1.49$, $p = .24$, $\eta_p^2 = .03$. Apart from the age-related difference in baseline performance, $F(1, 42) = 61.01$, $p < .001$, $\eta_p^2 = .59$, all interactions with age group (including the interaction with RSI, $F(1, 42) = 3.01$, $p = .10$, $\eta_p^2 = .06$) were non-significant when using log RTs, all ps > .23.

The ANOVA on error rates disclosed a main effect of task transition, $F(1, 42) = 12.38$, $p < .01$, $\eta_p^2 = .23$, reflecting alternation costs of 1.0% (switch trials: 1.8%; repetition trials: 0.8%). The interaction of task transition and RSI was non-significant, $F(1, 42) = 4.02$, $p = .051$, $\eta_p^2 = .09$, but there was a trend toward a reduction of error-related alternation costs with long RSI (1.5% vs. 0.5%). All other effects were not significant, too, all ps > .18.

In summary, we found a slowdown in general performance in older adults, as it is commonly observed in task-switching studies (e.g., Kray & Lindenberger, 2000). In line with findings about age-related effects in mixing costs (see, e.g., Wasylyshyn et al., 2011, for a review), we found an age-associated increase in alternation costs (even though it was not significant at the 0.05 level), but these costs were not disproportionally larger in old adults, and thus, general slowing as a potential explanation for age-related effects in these costs could not be excluded. Importantly, the RSI-based reduction of alternation costs did not differ across age groups.[4]

Experiment 2

In Experiment 1, we found an indication for an age-related increase in alternation costs and no age-associated differences in the preparatory reduction of these costs under situations

with low task-set competition. To explore whether task-set competition influences the size of age-related effects in these costs and in their preparatory reduction, we ran Experiment 2, in which we increased task-set competition by using bivalent instead of univalent stimuli.[5] Task-set competition results in interference, thus making the differentiation between task sets more difficult. As univalent stimuli are associated with just one task, they generate only one response, thereby resulting in low interference between task sets. In contrast, bivalent stimuli include features relevant to two tasks, and thus, can elicit two potential responses. Bivalent stimuli induce, due to the increased interference resulting from the activation of the competing stimulus-response rules, greater performance costs than univalent stimuli (e.g., Rogers & Monsell, 1995) and larger age-related effects therein (Mayr, 2001).

We expected performance to be slower and more error prone with bivalent stimuli, which should be reflected by increased alternation costs. Moreover, we assumed that older adults would suffer more from increased task-set competition and would therefore show larger alternation costs and, in contrast to the findings of Experiment 1, a smaller preparatory reduction of these costs than young adults.

Method

Participants. A new group comprising 22 young adults (11 women; range: 18-24 years; *M* = 22.4 years) and 22 older adults (11 women; range; 65-78 years; *M* = 71.1 years) participated in exchange for partial fulfillment of course requirements or financial compensation (8€). All participants gave informed consent, filled in a demographic questionnaire, and performed the DemTec. The age groups did not differ with regard to the educational level (young adults: 15.1 years; older adults: 14.0 years; two-tailed *t*-test: $t(42) = 1.08$, $p = .29$). All participants had normal or corrected-to-normal vision and they reported to be in good health and free of neurological diseases. The DemTec scores were comparable across age groups (young adults: 17.6; older adults: 17.1; two-tailed *t*-test: $t(42) = 1.01$, $p = .32$) and all participants were found to be within normal age-related limits (see Table 1).

Stimuli, tasks, and responses. We used digits (1 to 9, without 5) as stimuli. The tasks were to decide whether the digits were even or odd and to judge whether they were smaller or greater than 5. There was a fixed task sequence with a task switch after each trial. Digits appearing to the left of a centrally positioned fixation cross required a parity judgement and those occurring to the right of the fixation cross a magnitude judgement (counterbalanced across subjects). The response keys and the effectors were the same as in Experiment 1. The leftmost response of each hand was used either for the even or the smaller classification, and the rightmost response for the odd or greater classification.

Procedure and design. The procedure and the design were identical to those used in Experiment 1.

Results and discussion

We used identical outlier criteria (young adults: 1.6%; older adults: 1.8%) and error definitions as in Experiment 1. Data analyses were based on mean RT (see Figure 1) and error rates (see Table 2).[6]

The ANOVA on RTs yielded significant main effects of task transition, $F(1, 42) = 374.46$, $p < 0.001$, $\eta_p^2 = 0.90$, and RSI, $F(1, 42) = 89.54$, $p < .001$, $\eta_p^2 = .68$, resulting in alternation costs of 457 ms (switch trials: 1143 ms; repetition trials: 686 ms) and in an RSI effect of 83 ms (short: 956 ms; long: 873 ms). As indicated by a reliable interaction of task transition and RSI, $F(1, 42) = 20.56$, $p < .001$, $\eta_p^2 = .33$, alternation costs were reduced after a long RSI (492 ms vs. 422 ms).

As expected, there was also a main effect of age group, $F(1, 42) = 60.06$, $p < .001$, $\eta_p^2 = .59$, reflecting faster responses for young than for older adults (758 ms vs. 1070 ms). Moreover, the interaction of task transition and age group was significant, $F(1, 42) = 15.18$, $p < .001$, $\eta_p^2 = .27$, indicating that alternation costs were larger for older than for young adults (549 ms vs. 365 ms). The interaction of age group and RSI was not significant, $F(1, 42) = 0.60$, $p = .44$, $\eta_p^2 = .01$, and the three-way interaction of task transition, RSI, and age group fell just short of significance, $F(1, 42) = 3.15$, $p = .08$, $\eta_p^2 = .07$. However, the RSI-based reduction of alternation costs was numerically smaller for older adults than for young adults (42 ms vs. 98 ms). Separate 2 × 2 ANOVAs with the within-subject variables task transition and RSI showed that for young adults, the RSI based reduction of alternation costs was significant, $F(1, 21) = 20.19$, $p < .001$, $\eta_p^2 = .49$, whereas for older adults, the interaction of task transition and RSI was non-significant, $F(1, 21) = 3.76$, $p = .07$, $\eta_p^2 = .15$. However, for older adults, there was a numerical trend toward smaller alternation costs after a long RSI than a short RSI. Note that when using log RTs, apart from the main effect of age group, $F(1, 42) = 66.46$, $p < .001$, $\eta_p^2 = .62$, the interaction of task transition, RSI, and age group actually became significant, $F(1, 42) = 6.71$, $p < .05$, $\eta_p^2 = .14$. Hence, the RSI-based reduction of alternation costs was disproportionally smaller for older than young adults. All other age-related effects were non-significant when using log RTs, all *p*s > .31.

To better illustrate the difference in the preparatory reduction of alternation costs, we calculated the proportional preparation effect (in %), using the formula proposed by Lawo and colleagues (2012). To calculate the proportional preparation effect, we divided the preparation benefit for a trial type (mean RT $_{\text{short RSI}}$ − mean RT $_{\text{long RSI}}$) by the mean RT (0.5 ∗ [mean

RT $_{\text{short RSI}}$ − mean RT $_{\text{long RSI}}$]). Then, we subtracted the proportional preparation effect in repetition trials from that in switch trials. For young adults, the preparatory reduction of alternation costs (in proportional scores) was 9.1%; for older adults, it was 0.3% (see Figure 2).

---- Figure 2 ----

For the error rates, there was a main effect of RSI, $F(1, 42) = 5.58$, $p < .05$, $\eta_p^2 = .12$, with responses being more error-prone after a short RSI than a long RSI (3.1% vs. 2.4%). No other effects were significant, all *p*s > .40.

In summary, increasing task-set competition resulted in age-related differences in the preparatory reduction of alternation costs. This specific preparation deficit in old age cannot be explained on the basis of general slowing and confirms the findings by Lawo et al. (2012).

Comparing age-related effects across Experiment 1 and Experiment 2

To examine the impact of the stimulus valence on age-related effects in alternation costs more directly, we compared alternation costs across Experiment 1 and Experiment 2 by calculating a 2 × 2 × 2 × 2 ANOVA with the within-subjects variables task transition (switch trials vs. repetition trials) and RSI (100 ms vs. 600 ms) as well as the between-subjects variables age group (young vs. older adults) and stimulus valence (univalent vs. bivalent). In the following, to avoid redundancy, we report only effects including the stimulus valence variable (i.e., Experiment 1 vs. 2).[7]

There was a significant main effect of stimulus valence, $F(1, 84) = 42.69$, $p < .001$, $\eta_p^2 = .34$, indicating that the increase in the stimulus-elicited set competition resulted in longer RTs (univalent: 737 ms; bivalent: 914 ms). The interaction between stimulus valence and task transition was also reliable, $F(1, 84) = 89.76$, $p < .001$, $\eta_p^2 = .52$. Alternation costs occurring in the context of bivalent stimuli were larger than alternation costs resulting from univalent stimuli (457 ms vs. 164 ms). The interaction of stimulus valence and RSI was non-significant, $F(1, 84) = 0.47$, $p = .50$, $\eta_p^2 = .01$. However, the interaction of stimulus valence, task transition, and RSI was reliable, $F(1, 84) = 4.26$, $p < .05$, $\eta_p^2 = .05$. The RSI-based reduction in alternation costs was greater for bivalent stimuli than for univalent stimuli (70 ms vs. 31 ms).

Moreover, with univalent stimuli, the difference in overall alternation costs between young and older adults was 77 ms and with bivalent stimuli, it increased up to 184 ms, but the interaction of stimulus valence, task transition, and age group was non-significant, $F(1, 84) = 3.00$, $p = .09$, $\eta_p^2 = .04$ (log RTs: $F(1, 84) = 0.15$, $p = .69$, $\eta_p^2 = .01$). Importantly though, the four-way interaction of stimulus valence, task transition, RSI, and age group was significant for both mean RTs, $F(1, 84) = 4.64$, $p < .05$, $\eta_p^2 = .06$, and log RTs, $F(1, 84) = 4.15$, $p < .05$, $\eta_p^2 = .05$ (see Figure 2 for the preparatory reduction of alternation costs in proportional scores). Age-

related differences in the RSI based reduction in alternation costs were greater with bivalent stimuli than with univalent stimuli (56 ms vs. −26 ms), indicating that older adults show task-preparation deficits in particular when the task-set competition is increased, such as with bivalent stimuli. All other interactions with stimulus valence and age group were significant neither for the mean RT data, all *p*s > .14, nor for the log RT data, all *p*s > .16.

The ANOVA on error rates disclosed a main effect of stimulus valence, $F(1, 84) = 17.01$, $p < .001$, $\eta_p^2 = .17$, indicating more error prone responses with bivalent stimuli than with univalent stimuli (2.8% vs. 1.3%). All other effects including the valence variable were non-significant, all *p*s > .15.

To sum up, we found evidence for performance deteriorations due to an increase in stimulus-driven set competition. This increase resulted in larger alternation costs and, specifically, in age-related differences in the preparatory reduction of these costs, indicating that task-preparation deficits in old age occur especially when the differentiation between task sets is difficult, confirming recent findings by Lawo et al. (2012) on age-related preparation deficits when overall task-set competition is high.

General discussion

The aim of the present research was to examine the effect of task-set competition on the preparatory reduction of switching-related performance costs in old age. To this end, we compared age-associated differences in the preparatory reduction of alternation costs occurring in the context of univalent vs. bivalent stimuli (Experiment 1 vs. 2).

In Experiment 1 with univalent stimuli, age-related deficits in alternation costs were moderate and disappeared when using log RTs. Importantly, alternation costs were reduced with long RSI, but this reduction did not differ across age groups. Apart from the difference in overall speed between age groups, no age-related effect remained significant when using log RTs, suggesting a strong role of general slowing on age-related performance differences.

In Experiment 2 with bivalent stimuli, we found reliable age-associated effects in alternation costs. Importantly, an age-related task-preparation deficit was now found, which was significant when using log RTs, indicating that general slowing cannot account for this finding. Confirming the findings by Mayr (2001), a direct comparison of Experiments 1 and 2 revealed that increasing task-set competition results in performance deteriorations in terms of larger alternation costs and heightened age-related effects in these costs. Moreover, the comparison showed that task-set competition results in impaired task preparation in old age.

In the present experiments, we found a RSI-based reduction in alternation costs. Yet, in Experiment 2, in which we used bivalent stimuli, this reduction was larger for young than for

older adults. This finding conforms to that of Lawo et al. (2012), who explored task-switching performance under increased task-set competition and also found evidence for impaired task preparation in older adults. The existence of a task-preparation deficit in old age in the context of bivalent stimuli and the absence of this deficit in situations with univalent stimuli suggests, along with the findings of Lawo et al. (2012), that an increase in task-set competition has a negative impact on the older adult's ability to prepare for an upcoming task. Thus, older adults cannot prepare for a task switch as effectively as young adults when the internal differentiation between task sets is difficult, so that working memory demands are particularly increased.

Most existing studies on age-related effects in task preparation explored generally whether there are age-associated differences in the preparatory efficiency. In contrast to these studies, we investigated whether the preparatory efficiency in old age is influenced specifically by task-set competition. Hence, our goal was to isolate the effect of task-set competition on age-related differences in task-preparation effects.

The novel finding of the present study is that task-set competition at the level of stimuli represents a factor decreasing the preparatory efficiency in older adults. There are three possible explanations for this deficit. First, the age-related task-preparation deficit might result from impaired task-set updating abilities in old age. Second, task-set maintenance might be more difficult for older adults than for young adults. This would indicate that age-related differences in task preparation are not primarily due to impaired task-set updating abilities, but are rather due to impaired maintenance abilities in old age. Third, there might be an age-related decline in both abilities. However, there are many studies providing evidence that maintenance abilities are relatively intact in old age, whereas processing components of working memory declines with age (e.g., Bopp & Verhaeghen, 2005; Craik, 1977; Dobbs & Rule, 1989; Park et al., 2002). Moreover, for predictable task sequences, there is no evidence for passive decay of task sets in preparation intervals up to 600 ms (e.g., Rogers & Monsell, 1995). Thus, working memory maintenance and task-set dissipation seem to play no important role when task preparation is assessed in predictable task sequences with relatively short preparation intervals. This suggests that in the present study, age-related task-set updating deficits are the source for the reduced preparatory efficiency in old age.

Hence, our contribution to the literature on age-related deficits in task switching is that we identify a specific situation that hampers task-set updating in old age. Moreover, our findings indicate that differences in such situational characteristics might be the reason for the mixed findings about the effect of age on task preparation in the existing literature. For future

research, an important goal will be to further isolate the effect of age on task preparation by identifying further situational characteristics that influence task-set updating in old age.

The finding that task-set competition affects task preparation in older adults has important implications for theories on cognitive aging in general and in particular for accounts of process-specific limitations in old age. There were no age-related differences in the preparatory reduction of alternation costs in the context of univalent stimuli, indicating that in the case of low task-set competition, updating processes in working memory are not impaired by age. However, increasing task-set competition by using bivalent stimuli resulted in disproportionally reduced preparation effects in older adults. This provides evidence that there are process-specific limitations in old age, affecting the updating ability. For older adults, these findings mean that even when there is an impaired task-set updating ability in old age, they are able to compensate this deficit when task-set competition is weak, resulting in task-preparation effects comparable to those of young adults. Hence, situational characteristics, here in terms of task-set competition, seem to determine whether deficits in this ability can be compensated. In addition to global deficits in certain cognitive processes, theories of cognitive aging should also be able to account for such compensatory effects.

Apart from the finding of reduced preparatory efficiency in old age due to increased task-set competition, our study showed age-related effects in alternation costs. However, overall, alternation costs were not disproportionally larger in older than young adults, suggesting that general slowing may account to some part for the increased costs in the present study.

Mayr (2001) showed that age-related differences in task switching are large and disproportional when response-sets physically overlap. The age-related increase in performance costs resulting from conceptual overlap was similar to when there was no overlap between response sets. These findings are in line with other studies which failed to demonstrate age-related effects in mixing costs when using univalent or highly natural responses that eliminated the need of maintaining arbitrary S-R mappings in working memory (e.g., Bojko, Kramer, & Peterson, 2004; Brinley, 1965; Mayr & Kliegl, 2000; Salthouse, Fristoe, McGuthry, & Hambrick, 1998). In the present experiments, there was only conceptual response-set overlap. Hence, we may assume that age-related effects would have been even stronger if we had used physically overlapping task sets, which induce additional task-set competition at the level of responses.

Conclusions

The data suggest that preparatory deficits in the context of increased task-set competition contribute to age-related performance deficits. In fact, the preparatory reduction of switch-related performance costs may be a particularly sensitive measure of age-associated effects, provided that task-set competition is high and overall task selection difficulty is large.

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Footnotes

[1] Given an alpha of 0.05 and a sample size of 22 subjects per age group, the statistical power to detect large age-related differences in alternation costs and preparation effects (cohen's d = 0.80) was 0.84 (Faul, Erdfelder, Lang, & Buchner, 2007).

[2] In the present study, we used a small stimulus-set size because there is evidence that age-related differences in switching-related performance costs occur mainly in situations with small stimulus-set sizes (e.g., Kray & Eppinger, 2006; Kray, Karbach, & Blaye, 2012).

[3] Please note that Rogers and Monsell (1995) found RSI-based preparation effects in predictable task sequences only when they varied the RSI between blocks and not when they varied the RSI within blocks. However, in a similar study, De Jong (2000) observed preparation effects even with random RSIs. Hence, the type of the RSI manipulation does not seem to be a critical factor with regard to the occurrence of RSI-based preparation effects.

[4] Experiment 1 was conducted in combination with a dual-task experiment, which we do not report here. The order of these experiments was counterbalanced across subjects. An ANOVA with the additional between-subjects variable experiment order (Experiment 1 followed by the dual-task experiment vs. vice versa) showed that the findings of Experiment 1 did not differ depending on which experiment was performed first (all ps > .36).

[5] Experiment 2 was run in combination with a further task-switching experiment, in which we assessed mixing costs. However, since this experiment is not fully comparable with Experiment 1 and Experiment 2, we do not report the 'mixing cost' experiment here. The order of Experiment 2 and the 'mixing cost' experiment was counterbalanced across participants and an ANOVA with the between-subjects variable experiment order (Experiment 2 followed by the 'mixing cost' experiment vs. vice versa) showed that the experiment order did not affect the performance in Experiment 2 (all ps > .32).

[6] The use of bivalent stimuli enabled us to distinguish between incongruent trials and congruent trials, and hence, to additionally analyze age-related effects in congruency effects. A trial is incongruent when the stimulus evokes different responses for two tasks. In contrast, a trial is congruent when the stimulus requires the same key press in both tasks. Indeed, we found more

erroneous responses to incongruent stimuli than to congruent stimuli (congruency effect: 1.2%), $F(1, 42) = 5.05$, $p < .05$, $\eta_p^2 = .11$. However, this congruency effect was not modulated by age. For the RT data, the congruency effect was not significant, $F(1, 42) = 2.78$, $p = .13$, $\eta_p^2 = .06$. All interactions including congruency and age group showed *p*s > .26 in both error and RT data.

[7] Since we used the data of Experiment 1 and Experiment 2 twice (separate analysis of Experiment 1 and Experiment 2 as well as the data of both experiments in a joint analysis), the error probability might have been increased for the between-experiment comparison.

Table 1

Demographic information.

	n	Sex (% female)	Age range (in years)	Mean age (in years)	Education (in years)	DemTec scores
Experiment 1						
Young adults	22	50	20-28	22.5	15.3	17.6
Old adults	22	50	65-78	70.9	15.5	17.3
Experiment 2						
Young adults	22	50	18-24	22.4	15.1	17.6
Old Adults	22	50	65-78	71.1	14.0	17.1

Table 2

Task-switching performance in Experiment 1 and Experiment 2: Mean error rates (in percentage; SD in parenthesis) as a function of task transition (switch vs. repetition), response stimulus interval (RSI; 100 ms vs. 600 ms), and age group (young vs. older adults).

	Young Adults			Older Adults		
	RSI 100 ms	RSI 600 ms	RSI effect	RSI 100 ms	RSI 600 ms	RSI effect
Experiment 1						
Switch trials	2.2 (0.6)	1.8 (0.5)	0.4	2.4 (0.6)	0.7 (0.5)	1.7
Repetition trials	0.8 (0.3)	0.7 (0.3)	0.1	0.8 (0.3)	0.9 (0.3)	-0.1
Alternation costs	1.4	1.1		1.6	-0.2	
Experiment 2						
Switch trials	4.0 (0.6)	2.9 (0.6)	1.1	2.8 (0.6)	1.9 (0.6)	0.9
Repetition trials	3.5 (0.7)	2.8 (0.6)	0.7	2.2 (0.7)	2.2 (0.6)	0
Alternation costs	0.5	0.1		0.6	-0.3	

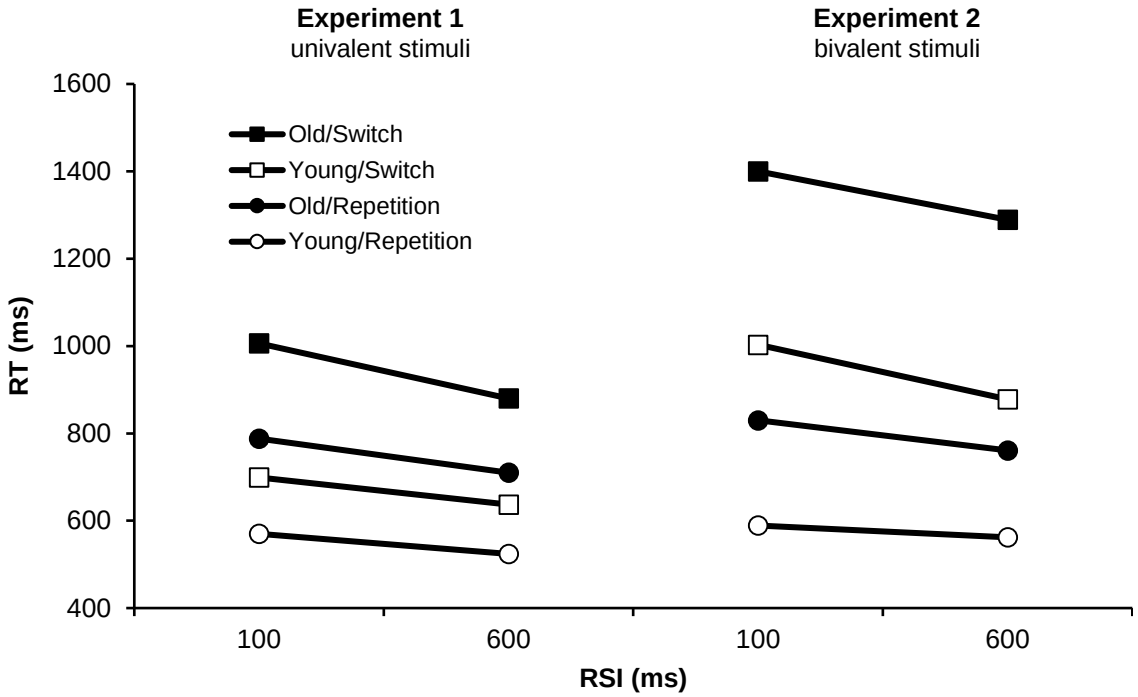

Figure 1. Task-switching performance in Experiment 1 and Experiment 2: Mean RTs (in ms) as a function of task transition (switch vs. repetition), response-stimulus interval (RSI; 100 ms vs. 600 ms), and age group (young vs. older adults).

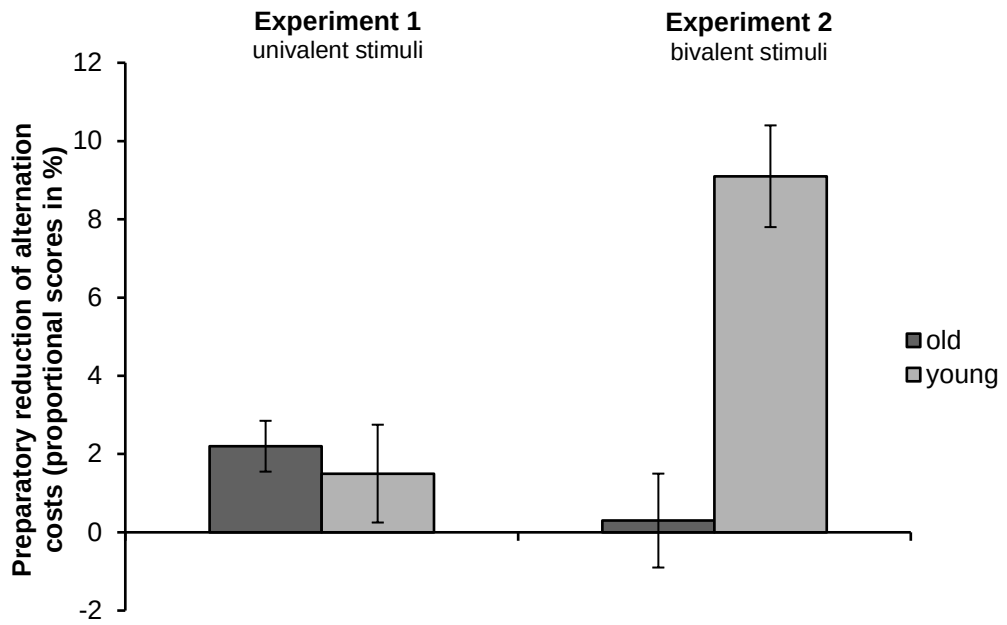

Figure 2. Preparatory reduction of alternation costs (proportional scores in %) in Experiment 1 and 2 as a function of age group (young vs. older adults). We first specified the proportional preparation effect by dividing the preparation benefit for a trial type ($RT_{short\ RSI} - RT_{long\ RSI}$) by the mean RT in this trial type ($0.5 * [RT_{short\ RSI} + RT_{long\ RSI}]$). Then, we calculated the preparatory reduction of alternation costs in proportional scores (in %) by subtracting the proportional preparation effect in repetition trials from that in switch trials. Error bars indicate the standard error of the mean.

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Common cognitive control processes underlying performance in task-switching and dual-task contexts.

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Common cognitive control processes underlying performance in task-switching and dual-task contexts

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Abstract

In the present study, participants performed on highly comparable task-switching and dual-task paradigms, and the paradigm-specific performance costs were analysed in the context of the commonly postulated core components of cognitive control (i.e., working memory updating, inhibition, and shifting). In the task-switching paradigm, we found switch costs (i.e., switch trials vs. repetition trials) and mixing costs (i.e., repetition trials in mixed-task blocks vs. single-task trials). In the dual-task paradigm, we observed a psychological refractory period (PRP) effect (i.e., Task 2 [T2] performance after short stimulus-onset asynchrony [SOA] vs. long SOA), dual-task costs (i.e., T2 dual-task performance with a long SOA in trials with a task repetition between Task 1 [T1] and T2 vs. single-task performance), and switch costs in T2 (i.e., dual-task performance in trials with a switch between T1 and T2 vs. dual-task performance in trials with a repetition between T1 and T2). A within-subjects comparison of the performance costs showed a correlation between mixing costs and dual-task costs, possibly indicating shared underlying cognitive control processes in terms of working memory updating. Surprisingly, there was also a correlation between switch costs and the PRP effect, presumably suggesting that cognitive control, as opposed to passive queuing of response selection processes, contribute to the PRP effect.

(209 words)

Keywords: cognitive control, task switching, dual tasks, PRP effect

Humans behave in a goal-directed and adaptive way in continuously changing environments. Such behaviour is enabled by cognitive control, a construct also referred to as executive function (see Cohen, 2017, for a discussion about the interchangeable use of 'cognitive control' and 'executive function'), which is responsible for the regulation of cognitive processing in accordance with current task goals (e.g., Logan, 2003). Cognitive processes involved in the updating of current task goals, in their shielding against irrelevant information and action tendencies, and in the dynamic switching between goals or foci of attention when there is a change in internal needs or environmental circumstances have been identified as core components of cognitive control (i.e., working memory updating, inhibition, and shifting; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000).

From this short summary it is evident that cognitive control is required during multitasking (Miyake et al., 2000). Multitasking is defined as the activity of performing several tasks within a limited time period, and hence, characterized by the temporal overlap of cognitive processes involved in performing multiple tasks. Thus, it refers to task-switching situations, in which we switch rapidly between tasks, and dual-task situations, in which we perform tasks more or less simultaneously. Experimental studies showed that multiple task-processing—both in terms of task switching and dual-tasking—results in performance costs relative to single-task processing (for reviews, see, e.g., Monsell, 2003; Pashler, 1994).

Performance costs occurring in multitasking contexts have been widely examined to get insights into cognitive control. As performance costs arising in task switching and dual tasks have been primarily discussed and explained independently of each other, little behavioural data is currently available that would allow for conclusions about whether the same or different cognitive control components underlie performance costs in task-switching and dual-task contexts (see Koch, Poljac, Müller, & Kiesel, in press, for a recent integrative review).

In the present study, we addressed this open question of common cognitive control components by conducting a within-subjects comparison across the performance costs arising in task-switching and dual-task contexts. To this end, we presented participants highly comparable task-switching and dual-task paradigms.

Cognitive control

Cognitive control enables complex cognition in non-routine situations such as in multitasking contexts. Miyake and colleagues (2000, 2012; see also Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003) identified working memory updating, inhibition, and shifting as three core components of cognitive control, which they defined as follows.

Updating refers to processes of monitoring incoming information for task-relevance and manipulating working memory content according to task goals by replacing content that is no longer relevant with task-relevant content. Thus, this component describes processes beyond the passive information maintenance by assuming that working memory content is revised to successfully respond to changing environmental demands.

Inhibition involves deliberate controlled processes responsible for the suppression of irrelevant information and responses. It refers to the ability to suppress memory intrusions that are no longer task-relevant, prepotent and automatic responses, as well as task-irrelevant stimuli to the task at hand (Friedman & Miyake, 2004).

Finally, shifting describes processes involved in the coordination of switching between various tasks, operations, and mental states (see, e.g., Kiesel et al., 2010, for a review). It is assumed to include the ability to engage and disengage appropriate task sets and to perform a new task in the context of proactive interference and negative priming (for proactive interference accounts, see, e.g., Allport, Styles, & Hsieh, 1994). Inhibition of the previously activated tasks, operations, and mental states as well as updating of task-relevant information in working memory appears to be a substantial prerequisite for shifting (Best & Miller, 2010; see, e.g., Koch, Gade, Schuch, & Philipp, 2010, for a review). The shifting component refers to the coordination of cognitive processes, such as inhibition and updating, in order to ensure successful switching.

These core components of cognitive control are related but dissociable according to Miyake et al. (2000). Against this background, the question arises as to which cognitive control components underlie performance in task-switching and dual-task contexts and whether performance in these contexts depends on shared components. A first step to answer this question is to examine the pattern of within-subjects correlations of performance costs across highly comparable task-switching and dual-task paradigms.

Similarities and differences between task switching and dual-tasking

The reason for the traditionally independent investigation of task switching and dual-tasking may be that task-switching and dual-task paradigms usually differ decidedly with respect to how the tasks are performed. In task-switching paradigms, costs of strictly serial switching from one task to another are measured by asking subjects to perform two successive tasks, thereby following an instructed (alternating-runs paradigm; e.g., Rogers & Monsell, 1995) or a random task sequence with a cue indicating the upcoming task to be performed (cuing-paradigm; e.g., Meiran, 1996). In contrast, in dual-task paradigms, such as the psychological refractory period (PRP) paradigm (see, e.g., Pashler, 1994, for a review), subjects

react with independent responses to two stimuli—Stimulus 1 (S1) and Stimulus 2 (S2)—which are presented with a varying stimulus onset asynchrony (SOA), and costs of performing two tasks—Task 1 and Task 2 (T2)—in temporal overlap are assessed.

Task switching

In the task-switching paradigm, performance costs are measured in terms of *mixing costs* and *switch costs* (for a review, see, e.g., Kiesel et al., 2010). Mixing costs are calculated by comparing performance in repetition trials of mixed-task blocks against trials in single-task blocks (see, e.g., Koch, Prinz, & Allport, 2005; Rubin & Meiran, 2005). In mixed-task blocks, subjects repeat and switch tasks across trials, constituting an experimental setting where two task sets have to be held active, and incoming information has to be monitored for task switches and thus for task-set updating. In contrast, single-task trials are performed in the context of constant task repetitions in order to obviate monitoring of incoming information to identify a task switch. Since none of the trial types contrasted in mixing costs have a switching requirement, the shifting component is held constant. Hence, mixing costs may mainly reflect working memory processes of task-set maintaining and updating (Mayr, 2001).

Switch costs are calculated as the performance difference between switch trials and repetitions trials of mixed-task blocks (e.g., Allport et al., 1994; Rogers & Monsell, 1995). In both trial types, incoming information has to be monitored with the objective of determining task switches and updating task sets. Switch trials require the disengagement and the engagement of tasks, whereas in repetition trials the same task can be applied again. Thus, switch costs may primarily reflect the shifting component (Miyake et al., 2000).

Switching-related performance costs are often accounted for by assuming that a task set has to be activated to perform a task, and that the task set has to be reconfigured (e.g., deletion of the previous task set, implementation of a new task set), when the task changes (task-set reconfiguration models; e.g., Meiran, 1996). Other researchers argue that to perform one of two tasks, it is necessary to inhibit the irrelevant task set. When the task switches, the persisting inhibition of the previously irrelevant task, but now intended task, and the persisting activation of the previously relevant, but now unintended task, have to be overcome (proactive interference models; e.g., Allport et al., 1994; see also Schuch & Koch, 2003).

Dual-tasking

In dual-task paradigms, performance costs are assessed in terms of the *PRP effect* and *dual-task costs*. The PRP effect is calculated in dual-task blocks as T2 performance difference across short and long SOAs (Pashler, 1994). Since in dual-task studies T1 usually differs from T2 (see, e.g., Hirsch, Declerck, & Koch, 2015; Lien, Schweickert, & Proctor, 2003, for

exceptions), the monitoring of information to update task sets in line with T2, as well as the disengagement and engagement of task sets in order to switch from T1 to T2, should be required regardless of the SOA. It thus remains unclear which specific component of cognitive control is isolated when comparing T2 performance across SOAs.

Dual-task costs are calculated by contrasting T2 performance in dual-task blocks with performance in single-task blocks. Since T2 performance in dual-task blocks includes costs evoked by the simultaneous selection of T1 and T2 responses, which are already reflected in the PRP effect, usually only performance after long SOAs is considered for the measurement of dual-task costs (see Halvorson, Ebner, & Hazeltine, 2013, for a discussion). Dual-task costs are assessed under conditions of varying working memory demands. In dual-task trials, two task sets have to be held active and incoming information has to be monitored to update task sets in accordance with T2, whereas in single-task trials, such monitoring processes are not necessary and only one task set has to be maintained. Thus, it is conceivable that like mixing costs, dual-task costs might primarily depend on working memory updating and task-set maintaining (see Miyake et al., 2000, for a similar hypothesis).

However, since in PRP studies, T1 usually differs from T2, the shifting component should also contribute to dual-task costs (Miyake et al., 2000). This is because in contrast to single-task trials, there is always the disengagement and engagement of task sets required when subjects switch from T1 to T2 in dual-task trials. Varying the task sequence within dual-task trials in such a way that there are switches and repetitions between T1 and T2 (e.g., T1-T2 switch: Task A [A] as T1 and Task B [B] as T2; T1-T2 repetition: B as T1 and B as T2) and using only T1-T2 repetitions for the assessment of dual-task costs enables the disentanglement of the updating and shifting component.

A link between the specific cognitive control components proposed by Miyake et al. (2000) and dual-task-related performance costs has not often been drawn. Instead, dual-task-related performance costs are usually explained by processing capacity limitations and/or by functional limitations of the cognitive system.

The most popular model on capacity limitations is the response-selection bottleneck model (e.g., Pashler, 1994). According to this model, it is structurally impossible to select two responses in parallel, which is why T2 response selection has to wait until the availability of an all-or-none bottleneck at the stage of response selection (i.e., full capacity is allocated to T1 and then to T2), postponing T2 response selection (i.e., increasing RT in T2, RT2) for the time during which the bottleneck is occupied by T1. Thus, this model accounts for dual-task-related performance costs without referring to any cognitive control processes.

Of late, this model has gone through various modifications, all of which maintain the idea of a processing bottleneck at the stage of response-selection. For example, Hommel (1998; see also Lien & Proctor, 2002; Schubert, Fischer, & Stelzel, 2008) proposed to subdivide the response-selection stage into an automatic response-activation stage occurring immediately after stimulus identification and activating task-relevant S-R mappings, and a final response-selection stage which can be occupied by one task only. With sufficiently short SOAs, the response activation stages overlap for T1 and T2, enabling T2 characteristics to affect the duration of the response-activation stage of T1. This modification enables the response-selection bottleneck model to account for a variety of findings observed in dual-task research (e.g., response-response compatibility effects; e.g., Fischer & Dreisbach, 2015; Hommel, 1998; Schuch & Koch, 2004).

In contrast, according to capacity sharing models (e.g., Tombu & Jolicoeur, 2003), response selection for two tasks may occur in parallel, but the processing capacity at the stage of response selection is limited. To optimize performance, response selection does not proceed in parallel for two tasks, but the capacity is allocated to the tasks in a graded manner, necessitating cognitive control processes for capacity scheduling.

Another line of models attributes dual-task-related performance costs to functional limitations (e.g., computational constraints) of the cognitive system (see, e.g., Fischer & Plessow, 2015, for a review). Such constraints occur when the same capacity is used 'for different purposes by multiple processes' (Feng, Schwemmer, Gershman, & Cohen, 2014, p. 130). For instance, in the ECTVA model (Logan & Gordon, 2001; see also the executive-process interactive control, EPIC, model; Meyer & Kieras, 1997), the PRP effect is due to a strategic decision for serial processing in order to resolve the dual-task-binding problem. This problem refers to the difficulty of distinguishing which response goes with which task when running the evidence accumulation process for two tasks in parallel. Thus, according to this model, T1 and T2 are performed serially, to minimize the risk of unwanted response reversal (see also Schubert, 2008, for a discussion on the role of order control in dual-tasking).

Temporal aspects of multitasking

Time intervals have a crucial impact on performance costs in both paradigms. The manipulation of the SOA is the key element of the PRP paradigm. The SOA defines the degree of temporal overlap in T1 and T2 processing. Task-switching experiments also offer the option of varying time components, including, among others, the response-stimulus-interval (RSI). The RSI determines the time period between the processing of tasks.[1]

Relating task switching and dual-tasking

At first sight, task-switching and dual-task paradigms appear to differ greatly from each other. However, in both paradigms, performance costs are affected by the duration of specific time intervals, and they are explained by assuming that there are cognitive processes prohibiting a strong parallel activation of two task sets on the one hand and a fully parallel response selection on the other (Koch et al., in press). However, switching-related performance costs and dual-task-related performance costs differ in the sense that they arise in task-switching paradigms under situations of strictly serial task-processing, whereas in dual-task paradigms they occur in situations of temporally overlapping task-processing.

Despite the commonalities between task switching and dual-tasking, there are only a few studies and theoretical considerations about how the performance costs in task switching and dual-tasking might be related (e.g., Band, Jolicoeur, Akyürek, & Memelink, 2006; Koch et al., in press; Oriet & Jolicoeur, 2003; Pashler, 2000; Sigman & Dehaene, 2006). For instance, by implementing T1-T2 switches and T1-T2 repetitions into dual-task trials, Band and van Nes (2006) as well as Lien et al. (2003) observed, in addition to a PRP effect, switch costs in T2. The cost was comparable across SOAs. Lien et al. (2003) concluded from the switch costs in T2 that time is needed for processes involved in the disengagement of T1 and the engagement of T2, and thus, that the shifting component is involved in dual-tasking (see also Liepelt, Strobach, Frensch, & Schubert, 2011, for similar conclusions derived from studies on practice effects in dual-tasking; for a review, see, e.g., Strobach & Schubert, 2017). They argued that the missing absorption of switch costs in T2 during the waiting period for the availability of the response-selection bottleneck (i.e., additivity of SOA and T1-T2 transition) suggests that these processes, at least partially, occur after response selection for T1 and before response selection for T2, and modified the response-selection bottleneck accordingly.

Using a latent variable analysis, Miyake and colleagues (2000) confirmed that the shifting component contributes to switch costs. However, they found dual-task costs to be not related to any of the core components and concluded cautiously, based on these null findings, that dual-task costs rely on an independent component of cognitive control which is not related to the proposed core components. Mixing costs, the PRP effect, and their underlying cognitive control components were not examined in their study.

In the present study, we assessed, besides switch costs and dual-task costs, mixing costs and the PRP effect to analyse these costs in the context of the core components of cognitive control. The goal was to identify shared and paradigm-specific cognitive control components

by measuring switching-related and dual-task-related performance costs in highly comparable paradigms and analyzing cross-paradigm correlations between them.

The present study

To examine whether performance costs in task-switching and dual-task paradigms have a common source, we designed a task-switching and dual-task paradigm as similarly as possible using the same stimuli, tasks, and responses. In the task-switching paradigm, subjects performed single-task and mixed-task conditions with a short and long RSI, whereas in the dual-task paradigm subjects performed single-task and dual-task conditions with a short and long SOA. The dual-task conditions included both T1-T2 switches and T1-T2 repetitions. With these highly comparable paradigms, we measured the paradigm-specific performance costs, and in order to gain first insights into paradigm-specific and common cognitive control components we subjected the costs to a correlation analysis (see e.g., Declerck, Grainger, Koch, & Philipp, 2017, for the use of correlation analyses in the study of shared cognitive control processes involved in task switching and language switching).

In the task-switching paradigm, we assumed to find mixing costs and switch costs. In the PRP paradigm, we expected a PRP effect, T2 switch costs, and dual-task costs. Regarding dual-task costs, we argue that T2 performance in T1-T2 repetition trials represents a more appropriate condition to be compared with single-task conditions. Our rationale is that in T1-T2 repetitions, T2 performance is unaffected by task switches, like the performance in single-task trials. Therefore, we calculated dual-task costs by contrasting T2 performance in T1-T2 repetition trials with single-task performance, thereby considering only trials with a long SOA. Moreover, we hypothesized a positive correlation between mixing costs and dual-task costs, possibly reflecting shared underlying cognitive control processes in terms of WM updating. In the literature a specific cognitive control component contributing to the PRP effect has not yet been identified. Therefore, hypotheses about the PRP effect and its relation to other performance costs cannot be clearly derived at the current point.

Method

Participants. Thirty-two participants (29 women, age range: 17-38 years; M = 22.7 years) took part in the experiment. One additional participant was tested, but because of an excessive error rate of > 45%, the data was replaced by a new data set, leaving 32 data sets for the analyses. All participants had normal or corrected-to-normal vision.

Stimuli, tasks, and responses. The stimulus material consisted of a fixation cross (+), an asterisk, digits from *1* to *9* (except *5*), and capital letters, including the consonants *G, K, M,* and *R* as well as the vowels *A, E, I,* and *U*. The stimuli were presented in white 20-pt. Arial font

on a black screen placed at a distance of approximately 50 cm. The fixation cross was presented at the centre of the screen, where it stayed throughout the entire experiment. Digits and letters were displayed 3 cm to the left and to the right of the fixation cross.

Subjects were asked to categorize digits as odd or even and letters as consonant or vowel. They used their index or the middle finger of the hand corresponding to the stimulus presentation location for response execution. Responses to stimuli appearing to the left of the fixation cross were made with the *Y* and *X* keys of a QWERTY keyboard. The *N* and *M* keys were used as response keys for stimuli presented to the right of the fixation cross. The S-R mapping for both tasks was counterbalanced across participants.

Procedure. The experiment was run in a single session, with one participant at a time, and took about 60 min. Instructions were given both in verbal and in written form, and emphasized speed and accuracy. The experiment consisted of a task-switching and a dual-task part with counterbalanced order across participants. Both the task-switching and the dual-task part comprised the following experimental blocks in the stated order—one single-task block of 41 trials for each task type, four mixed-task blocks in the task-switching part or dual-task blocks in the dual-task part, of 81 trials each, and one single-task block of 41 trials for each task type. The first single-task blocks were preceded by practice blocks of six trials, and the first mixed-task or dual-task blocks were preceded by a practice block of 12 trials. Importantly, the task type for the first single-task block was counterbalanced across subjects.

In the *task-switching part*, the stimuli appeared alternately to the left and right of the fixation cross, starting at the left side. They remained on the screen until a response was executed. The next stimulus was displayed after a random RSI of 100 ms or 600 ms.

In single-task blocks of the *dual-task part*, an asterisk, which served as task-irrelevant S1, appeared to the left of the fixation cross, followed by a task-relevant S2 to the right of the fixation cross after a random SOA of 100 ms or 600 ms. In dual-task blocks, the asterisk was replaced by a task-relevant S1. Both stimuli disappeared after T2 response execution. The next trial began 1,000 ms later (inter-trial interval, ITI).

The stimulus presentation was random with the restriction that all stimuli were displayed equally often (i.e., when including also practice trials) and that there were no immediate stimulus repetitions.[2] In the dual-task part, S1 and S2 varied independently of each other. However, we controlled that the number of repetitions and switches between T2 of the previous trials and T1 in the current trial was the same.

Design. For the task-switching part, we specified two non-orthogonal 2 × 2 contrasts, including a mixing-cost contrast and a switch-cost contrast. The independent within-subject

variables were RSI (100 ms vs. 600 ms) and trial type. In the mixing-cost contrast, we contrasted performance in repetition trials of mixed-task blocks with that in single-task trials, whereas in the switch-cost contrast, we compared performance in switch trials with that in repetition trials.

For the dual-task part, we analysed the effects of T1-T2 sequence and SOA separately for T1 and T2 based on a 2 × 2 repeated-measures design with the independent within-subject variables T1-T2 sequence (T1-T2 switch vs. T1-T2 repetition) and SOA (100 ms vs. 600 ms). Finally, to measure dual-task costs, we contrasted performance across single-task trials and dual-task trials with long SOA which included a task repetition between T1 and T2.

To deal with speed-accuracy trade-offs with respect to the main effects of RSI and SOA and with respect to the interaction of RSI and trial type, we do not report separate analyses for RT and error rates but linear integrated speed-accuracy scores as the dependent variable (LISAS; Bruyer & Brysbaert, 2011; Vandierendonck, 2017). LISAS integrate speed and accuracy, resulting in RT scores that are corrected for the number of errors committed (for the mean RT data and the error data, see Table 1 in the Appendix).

Results and discussion

Practice blocks, the first trial in each block, and trials following an error were eliminated from all data analyses. Trials with an erroneous response and trials deviating more than 3 *SD* from each individual's mean RT per condition (task switching part: 1.9% of single-task trials, 2.0% of mixed-task trials; dual-task part: 1.9% of single-task trials, 1.9% of T1 in dual-task trials, and 2.0% of T2 dual-task trials) were additionally discarded from the RT analysis. We report the results separately for the task-switching and the dual-task part (see Figure 1 and Figure 2), followed by a joint analysis for correlations.

----Figure 1 and Figure 2----

Task-switching performance. We analyzed task-switching performance based on two contrasts, one mixing-costs contrast and one switch costs contrast. We first report the results for the mixing costs contrast and then those for the switch costs contrast.

Mixing costs. There were significant main effects of trial type, $F(1, 31) = 10.31$, $p < .01$, $\eta_p^2 = .25$, and RSI, $F(1, 31) = 61.87$, $p < .001$, $\eta_p^2 = .67$. RTs were higher in repetition trials of mixed-task blocks than in single-task trials (800 ms vs. 733 ms) and with short RSI than with long RSI (807 ms vs. 726 ms), reflecting mixing costs of 67 ms and a RSI effect of 81 ms. The interaction of trial type and RSI was non-significant, $F < 1$.

Switch costs. There was a significant main effect of trial type, $F(1, 31) = 11.06$, $p < .01$, $\eta_p^2 = .26$, indicating slower responses in switch trials than in repetition trials (836 ms vs. 800 ms; switch costs: 36 ms). The main effect of RSI was significant, too, $F(1, 31) = 47.19$, $p <$

.001, η_p^2 = .60. Responses were slower with short RSI than with long RSI (860 ms vs. 776 ms; RSI effect: 84 ms). The interaction of trial type and RSI was non-significant, $F < 1$.

Dual-task performance. For the dual-task part, we analyzed the T1 and T2 performances separately. Moreover, we contrasted T2 performance (i.e., T1-T2 repetitions with long SOA) with single-task performance. We first report the results for T1 and T2, followed by the performance comparison across T2 of dual-task conditions and single-task conditions.

T1. For T1, there was no main effect of T1-T2 sequence, $F < 1$. However, the main effect of SOA was significant, $F(1, 31) = 7.11$, $p < .05$, $\eta_p^2 = .19$, reflecting faster responses with short SOA than with long SOA (932 ms vs. 968 ms). Moreover, there was a non-significant trend towards an interaction of T1-T2 sequence and SOA, $F(1, 31) = 2.99$, $p = .09$, $\eta_p^2 = .09$, suggesting faster responses with short than with long SOA in repetition trials (924 ms vs. 977 ms; $t(31) = -2.93$, $p < .01$, $d = 0.14$), but no RT differences across SOAs in switch trials (939 ms vs. 959 ms; $t(31) = -1.38$, $p = .18$, $d = 0.06$).

T2. For T2, there was a significant main effect of T1-T2 sequence, $F(1, 31) = 16.60$, $p < .001$, $\eta_p^2 = .35$, reflecting slower responses in T1-T2 switch trials than in T1-T2 repetition trials (1220 ms vs. 1139 ms), and thus, switch costs in T2 of 81 ms. Moreover, the main effect of SOA was significant, $F(1, 31) = 141.46$, $p < .001$, $\eta_p^2 = .82$. Responses were slower with short SOA than with long SOA (1575 ms vs. 784 ms; PRP effect: 791 ms). The interaction of T1-T2 sequence and SOA was non-significant, $F < 1$.

Dual-task costs. An one-tailed *t*-test showed that in trials with a long SOA, responses were slower in T1-T2 repetition trials than in single-task trials (747 ms vs. 610 ms), $t(31) = 3.18$, $p < .01$, $d = 0.65$, resulting in dual-task costs of 137 ms.

Interim summary

To summarize, in the task-switching part, we observed mixing costs and switch costs. Performance was worse with short than with long RSI. However, there was no effect of RSI on mixing costs and switch costs. In the dual-task part, we observed an SOA effect in T1[3], a PRP effect, dual-task costs and switch costs in T2. Switch costs in T2 were about the same size across SOAs, possibly indicating that task-set reconfiguration or/and the modification of task-set activation levels take place after response selection for T1 (for an accordingly modified response-selection bottleneck model, see Lien et al., 2003).

Comparison of paradigm-specific costs

We obtained performance costs in both paradigms. To examine whether there is a relationship between these paradigm-specific performance costs, suggesting overlapping cognitive control processes, we calculated mixing costs, switch costs, dual-task costs (i.e., dual-

task performance with long SOA), switch costs in T2, and the PRP effect (i.e., averaged over T1-T2 switches and repetitions) individually for each participant and subjected them to a correlation analysis (see Table 1).

----Table 1----

Across paradigms, there was a significant relationship between mixing costs and dual-task costs, $r(32) = .43$, $p < .05$ (see Figure 3), indicating that the magnitude of mixing costs increased with increasing dual-task costs. Furthermore, mixing costs correlated positively with the PRP effect, $r(32) = .49$, $p < .01$, and with switch costs in T2, $r(32) = .67$, $p < .001$. The correlation between switch costs and the PRP effect was also significant, $r(32) = .63$, $p < .001$. Switch costs increased when the PRP effect increased (see Figure 4). Surprisingly, this correlation remained significant, even when using only T1-T2 repetitions for the calculation of the PRP effect, $r = .59$, $p < .001$. Moreover, switch costs were related to switch costs in T2, $r(32) = .64$, $p < .001$.

----Figure 3 and Figure 4----

Regarding the relationships between performance costs measured within the same paradigm, we found positive correlations between mixing costs and switch costs, $r(32) = .48$, $p < .01$, and between the PRP effect and switch costs in T2, $r(32) = .60$, $p < .001$. Moreover, there was a trend towards a relationship between dual-task costs and the PRP effect, $r(32) = .35$, $p = .051$.

Discussion

In the present study, we evaluated correlations between the performance costs arising in task-switching and dual-task paradigms, to examine whether shared cognitive control components underlie performance impairments in these multitasking contexts. In the *task-switching part*, we found mixing costs and switch costs. In the *dual-task part*, we observed dual-task costs, a PRP effect, and switch costs in T2. In line with our hypothesis, there was a positive correlation between mixing costs and dual-task costs. Moreover, there were correlations between switch costs, switch costs in T2, and the PRP effect.

Underlying mechanisms of task-switching and dual-task performance

Cognitive control enables successful performance in task-switching and dual-task contexts (Meyer & Kieras, 1997). The current study did not allow specifying these cognitive control processes directly; however, it was possible to explore whether the observed performance costs rely on related or unrelated components of cognitive control.

Task-set shifting. The correlation analysis showed that switch costs in the task-switching part correlated with switch costs in T2 and the PRP effect. Like switch trials in the

task-switching part, T1-T2 switch trials in the dual-task part possibly also require a task-set shift, more specifically between the task set of T1 and that of T2. This implies that by contrasting performance across T1-T2 switches and repetitions, and thus by calculating switch costs in T2, the shifting component might be isolated. Given that switch costs in the task-switching part and the dual-task part are indices of the shifting component of cognitive control, the correlations between switch costs, switch costs in T2, and the PRP effect might indicate that the shifting component contributes to the PRP effect.

Importantly, the effects of SOA and task transition in T2 were additive, reflecting comparable switch costs in T2 across SOAs. For response-selection bottleneck models, this finding means that shifting occurs after response selection for T1 and before response selection for T2, requiring shifting processes to wait until the response for T1 is selected with both short and long SOAs, thus impairing T2 performance across SOAs to the same degree. Considering such processing streams for T1 and T2, the effect of shifting should be eliminated and performance differences across SOAs should only be attributable to passive response-selection queuing after subtracting T2 performance with long SOA from that with short SOA. Hence, a response-selection stage without any shifting processing and a following stage responsible for the complete task-set shift procedure cannot account for the correlation of the PRP effect with markers of the shifting component.

This conclusion is further reinforced by the observation that the correlation of switch costs and the PRP effect remained significant, when using only T1-T2 repetition trials for the calculation of the PRP effect. This correlation suggests that, even when a task is repeated across T1 and T2, two separate task sets have to be activated (i.e., the same task set twice; e.g., Logan & Gordon, 2001), and that switching between different components of these task sets (e.g., response mappings) is necessary to perform T1 and T2 in a temporal overlap (e.g., Duncan, 1995). This finding clearly contradicts the assumptions by Pashler (2000) who argued that the passive queuing of the response selection for T2 is the single source of the PRP effect and that the occurrence of the PRP effect in trials where a task is repeated across T1 and T2 speaks against the involvement of shifting processes.

Response inhibition. PRP trials with a short SOA, where two stimuli are presented almost simultaneously, resemble bivalent stimuli in task switching, thereby also affording the application of the competing task. Thus, when there is a response-set overlap, such as the conceptual overlap in the present study, they also activate the competing response, thereby exogenously cueing between-task competition and crosstalk (e.g., Kiesel et al., 2010; Koch et al., in press).

In PRP studies, response-response (R-R) compatibility effects are usually interpreted as empirical evidence for competition between T1 and T2 (e.g., Fischer & Dreisbach, 2015; Hommel, 1998; Schuch & Koch, 2004). They are measured as the performance decrement in R-R incompatible trials (i.e., response switch; e.g., left key in T1 and right key in T2) compared to R-R compatible trials (e.g., response repetition; e.g., right key in T1 and T2).

To explore if competition between T1 and T2 contributed to the PRP effect, we ran an additional analysis with the independent variables T1-T2 sequence, SOA, and R-R compatibility. Whereas there was no effect of R-R compatibility on T1 performance, all *p*s > .38, the interaction of T1-T2 sequence and R-R compatibility was significant for T2, $F(1, 27) = 17.18$, $p < .001$, $\eta_p^2 = .40$ (all other *p*s > .23). In repetition trials, responses were slower with R-R incompatible than with R-R compatible trials (1187 ms vs. 1109 ms; R-R compatibility effect: 78 ms, post-hoc one-tailed *t*-test: $t(27) = 2.43$, $p < .05$, $d = 0.17$). In switch trials, however, the opposite data pattern was observed (1278 ms vs. 1208 ms; reversed compatibility effect: 70 ms, post-hoc one-tailed *t*-test: $t(27) = -3.07$, $p < .01$, $d = 0.14$).

In numerous task-switching studies, R-R compatibility, in this domain referred to as response repetition, has also been observed to be beneficial when the task is repeated and detrimental when the task is switched (e.g., Koch, Frings, & Schuch, 2017; Koch, Schuch, Vu, & Proctor, 2011; Schuch & Koch, 2010). Several models have been proposed to account for this interaction (cf., Druey, 2014; Rogers & Monsell, 1995).

One group of models that is linked to the inhibition component of cognitive control (e.g., Druey & Hübner, 2008) is especially important in the context of the present study. These models postulate that to prevent perseveration tendencies, responses are inhibited immediately after being selected. According to these models, there are no response-repetition costs in task repetition trials because response repetitions within task repetition trials are accompanied by a stimulus-category repetition that primes the inhibited response, which, in turn, weakens the inhibition, leading to improved performance relative to switch trials. Response repetitions in switch trials are not accompanied by a stimulus-category repetition, so that the inhibition has to be overcome.

These mechanisms of response inhibition and stimulus-category priming can be transferred from serial task processing to temporally overlapping task processing. The opposite effects of R-R compatibility across T1-T2 switches and repetitions, along with its independency from SOA, suggest that T1 response inhibition might be a part of either the response-selection stage or of an additional stage that follows T1 response selection and postpones T2 response

selection until the response for T1 is inhibited (see also ECTVA model by Logan & Gordon, 2001).

Importantly, there was also an interaction of task sequence and response sequence (i.e., R-R compatibility) in the task-switching part, $F(1, 31) = 4.89$, $p < .05$, $\eta_p^2 = .14$. Response repetition led to a cost, more so in task-switch trials (878 ms vs. 835 ms) than in task-repetition trials (822 ms vs. 811 ms). Post-hoc one-tailed *t*-tests showed that response repetition-costs were significant for task-switch trials, $t(31) = 3.43$, $p < .01$, $d = 0.18$, but non-significant for task-repetition trials, $t(31) = 0.83$, $p = .21$, $d = 0.05$. The lacking response- repetition effect in task repetitions might be accounted for by the use of univalent stimuli which have been shown to exhibit weaker effects of response sequence than bivalent stimuli (e.g., Grzyb & Hübner, 2013; Hübner & Druey, 2006). In this light, it is conceivable that the correlation between the PRP effect and switch costs reflects stimulus-category priming in combination with response inhibition. However, since there was no response-repetition benefit in task repetitions of the task-switching part, further research is needed in this context.

Response inhibition and stimulus-category priming, however, cannot account for the correlation of dual-task costs and mixing costs. As indicated by R-R compatibility effects (106 ms; two-tailed *t*-test: $t(27) = 3.06$, $p < .01$, $d = 0.35$), there was between-task competition in T1-T2 repetition trials with long SOA. In contrast, in single-task trials, only one stimulus was presented, eliminating the potential effects of bivalent stimuli. Thus, dual-task costs might be inflated by mechanisms involved in the resolution of between-task competition (Koch, 2009). In the task-switching part, there was, however, no effect of the response sequence on task repetition trials which are used for the calculation of mixing costs.

Note that we did not assess direct markers of inhibitory control in the present study. In the task-switching domain, there is converging evidence that inhibition is involved in task-switching performance (e.g., Mayr & Keele, 2000; for a review, see, e.g., Koch et al., 2010). In dual-task research, however, inhibition has not yet been examined systematically (see Hirsch, Nolden, & Koch, 2017, for an exception), thus remaining an important topic for future studies.

Working memory updating. The correlation analysis showed a positive relationship between mixing costs and dual-task costs, thereby indicating that these costs might rely on overlapping cognitive control processes. These costs represent performance differences between conditions in which monitoring of incoming information is necessary and conditions in which no monitoring of incoming information is required. Thus, mixing costs and dual-task costs reflect presumably cognitive control processes in terms of task-set updating.

However, by employing univalent stimuli (i.e., stimuli linked to one task), we could not exclude the alternative explanation that subjects built a combined task-set comprising stimulus-response mappings for the digit and letter tasks simultaneously (e.g., Kleinsorge & Heuer, 1999). In this case, mixing costs would reflect higher working memory load in mixed-task blocks compared to single-task blocks, and the correlation between mixing costs and dual-task costs would rather be due to the working memory load than task-set updating. The use of univalent stimuli in the dual-task part allowed us to study the effects of T1-T2 sequence in a traditional PRP procedure without cues. Future studies should replicate the findings of the present study based on a design that allows, despite the use of a traditional PRP procedure, the application of bivalent stimuli in the task-switching and the dual-task paradigm.

Note that mixing costs as a marker of working memory updating were also related to switch costs, switch costs in T2, and the PRP effect, which are assumed to rely on the shifting component. These correlations might indicate difficulties in isolating experimentally the shifting component in switch conditions. Successful task switching requires the monitoring of incoming information to determine task switches and update task-sets in accordance with new tasks. Based on this line of argument, switch costs, switch costs in T2 and the PRP effect should, in addition to the shifting component, also rely on the updating component.

Nevertheless, the question remains why only mixing costs, and not dual-task costs, were related to performance costs that depend on the shifting component. One explanation is that, in addition to the updating component, mixing costs also measure other processes of cognitive control that are not reflected in dual-task costs, which, however, contribute to task-switching performance.

A further explanation might be related to the differences in the experimental settings. One such a difference is that in the dual-task part the two trials are separated by long ITIs, while in the task-switching part the tasks are performed in rapid succession, inducing strong between-task interference even in repetition trials. In this regard, it might be possible that, in contrast to T1-T2 repetitions, monitoring and updating occurs in repetition trials of mixed-task blocks under processing demands that are more similar to that in switch conditions. In the present study, we could only speculate on this point, meaning that more research is required.

Additional factors and their relation to other studies. In line with the present study, Miyake and colleagues (2000) proposed that shifting contributes to switch costs. However, they found dual-task costs to be independent of all three core components, thus drawing the conclusion that, in contrast to task-switching performance, dual-task performance might rely on cognitive control mechanisms that are not related to the examined three core components.

In contrast, we concluded based on our findings from an empirical approach in terms of a cross-paradigm correlation analysis between performance costs measured in highly comparable task-switching and dual-task paradigms that the core components of cognitive control are involved in dual-task performance, at least in terms of working memory updating and shifting, as indicated by the correlations between mixing costs and dual-task costs, and between switch costs and switch costs in T2 of the dual-task part.

The contradictory findings regarding the role of the core components of cognitive control for dual-task costs might be accounted for by the use of different task types. Whereas Miyake et al. (2000) used two continuous tasks (i.e., maze tracing speed test and word generation task) to be performed over several minutes and measured the number of correctly solved tasks. We employed two discrete tasks with an identical number of tasks per subject, and assessed RT and errors. Discrete tasks have a definitive observable start and end point (i.e., stimulus onset and response execution; Salvucci, 2005), and are usually separated by an ITI, allowing performance to be analyzed on a fine-grained trial-by-trial level.

In this context, Pashler and Johnston (1989) argued that, in contrast to discrete tasks, analysing performance on continuous tasks has a limited contribution to the theoretical understanding of the causes of dual-task interference because simultaneous task processing cannot be distinguished from a strategy of switching between tasks when focusing solely on the number of correctly solved tasks. On the other hand, continuous tasks have the advantage over discrete tasks that they allow for the investigation of feedback and error correction. Thus, discrete and continuous tasks can be used to study different aspects of dual-task processing, which possibly are also differently related to the core components of cognitive control.

Use of integrated speed-accuracy measures

The use of integrated measures is especially well suited when speed and accuracy are assumed to be driven by overlapping processes. Task switching and dual-tasking have been shown to result in performance costs in both speed and accuracy. This indicates that both these performance measures rely on the same processes (e.g., Halverson et al., 2013; Han & Marois, 2013; Meiran, 1996). Apart from response-selection bottleneck models that predict a PRP effect only in the RT (e.g., Pashler, 1994), dual-task models, such as the capacity sharing model (Tombu & Jolicoeur, 2003) and the ECTVA model (Logan & Gordon, 2001), can account for SOA effects in RTs and error rates, thus justifying the use of integrated measures. Moreover, integrated measures have already been used in the task-switching domain (e.g., Draheim, Hicks, & Engle, 2016; Schuch & Pütz, in press) and the dual-task domain (Han & Marois, 2013; Kunde, Pfister, & Janczyk, 2012).

Summary and conclusions

In sum, the present study represents a first step towards understanding the relationship between the cognitive control components involved in task-set control by providing evidence that mixing costs and dual-task costs might be markers of working memory updating and switch costs and switch costs in T2 might be indices of the shifting component, but partly also of the updating component. Notably, we also found that the PRP effect correlated substantially ($r > .5$) with switch costs, suggesting that the PRP effect is related to shifting processes rather than being purely based on passive response queuing processes. The present study also showed that performance costs in multitasking do not measure the components of cognitive control in an isolated and differentiated manner. This is in line with the conclusion by Miyake et al. (2000), who argued that the components of cognitive control are related as well as separable. Future studies need to extend these conclusions to multitasking contexts using different types of tasks in order to establish the generality of the present conclusions. In this connection, it would also be important to focus on inhibition and to use bivalent stimuli in order to exclude working memory load as an alternative explanation for the correlation between mixing costs and dual-task costs.

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Footnotes

[1] The manipulation of specific time intervals enables the investigation of task preparation in task switching. Preparation is analyzed by manipulating the RSI in the alternating-runs variant and by varying the cue-stimulus interval (CSI; i.e., time interval between the onset of the task cue and the presentation of the target stimulus) in the cuing variant. Reduced switch costs with long RSIs compared to short RSIs can be attributed to both active preparation for the upcoming task and decay of activation related to the preceding task. In the cueing variant, active preparation can be isolated by varying the RCI inversely to the CSI, while activation decay of the previous task can be isolated by varying the RCI and holding the CSI constant (see Kiesel et al., 2010, for a review). In the alternating-runs variant, subjects have to keep track of the task sequence, representing an additional working memory requirement. Here, preparation for the upcoming task can proceed immediately after response execution to the current task, and switching is driven internally. In contrast, in the cueing variant of the task-switching paradigm, switching is driven by external cues and there are no demands relating to the maintenance of the task sequence but on cue encoding. Moreover, task preparation has to wait until the presentation of the cue. Thus, these task-switching variants allow the isolation of different types of task preparation.

[2] Note that owing to the avoidance of immediate stimulus repetitions, the likelihood of response (side) repetitions and response (side) switches differed across task-switch trials and task-repetition trials. Task-switch trials were associated with eight stimuli, and thus, there was a 50:50 chance of the correct response. In contrast, task-repetition trials were associated only with seven stimuli because the stimulus displayed in the previous trial could not be presented again. Thus, in task-repetition trials, there was a larger likelihood for a response (side) switch than for a response (side) repetition. Implicit learning of the stimulus presentation, therefore, might have influenced switch costs by improving performance in task repetition trials.

[3] To explore whether faster responses with short than with long SOA were due to response grouping, we analyzed the time intervals between the response for T1 and that for T2 (i.e., inter-response interval; IRI). We defined IRIs less than 100 ms as indicative for response grouping (e.g., Miller & Ulrich, 2008). Overall, there were 9.5% trials with an IRI less than 100 ms. When excluding trials with grouped responses, the data pattern did not change, except that the

trend towards an interaction of T1-T2 sequence and SOA in T1 became significant, $F(1, 31) = 6.05$, $p < .05$, $\eta_p^2 = .16$. Thus, the main effect of SOA was not due to response grouping.

Table 1

Correlation coefficients between performance costs assessed in the task-switching (TS) part and performance costs measured in the dual-task (DT) part for LISAS.

	Mixing costs in TS	Switch costs in TS	Dual-task costs in DT	T2 switch costs in DT	PRP effect in DT
Mixing costs in TS	1	.48**	.43*	.67***	.49**
Switch costs in TS		1	.27	.64***	.63***
Dual-task costs in DT			1	.42*	.35
T2 switch costs in DT				1	.60***
PRP effect in DT					1

Note. *$p < .05$, **$p < .01$, and ***$p < .001$. PRP = Psychological Refractory Period.

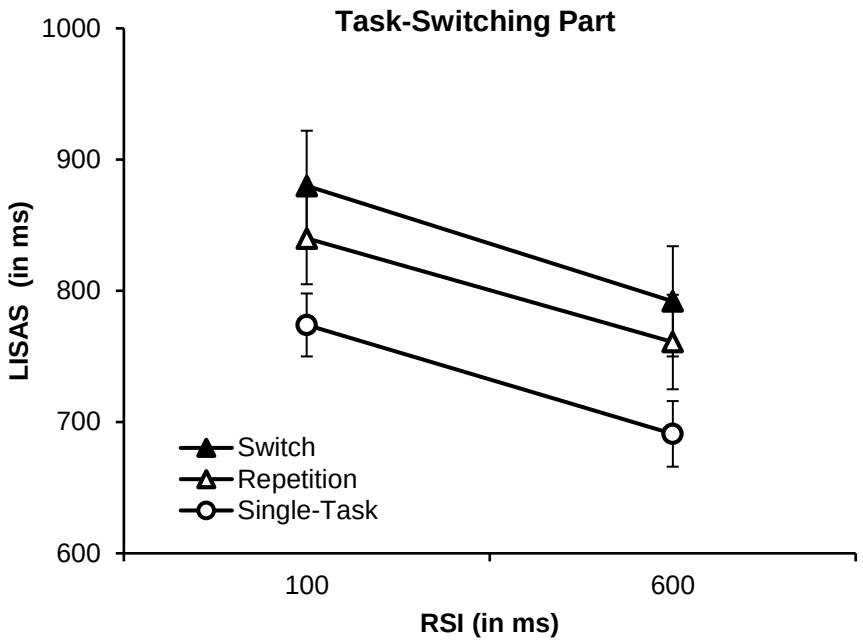

Figure 1. LISAS (in ms) in the task-switching part as a function of trial type (switch trials, repetition trials, and single-task trials) and response stimulus interval (RSI; 100 ms vs. 600 ms). Error bars represent the standard error.

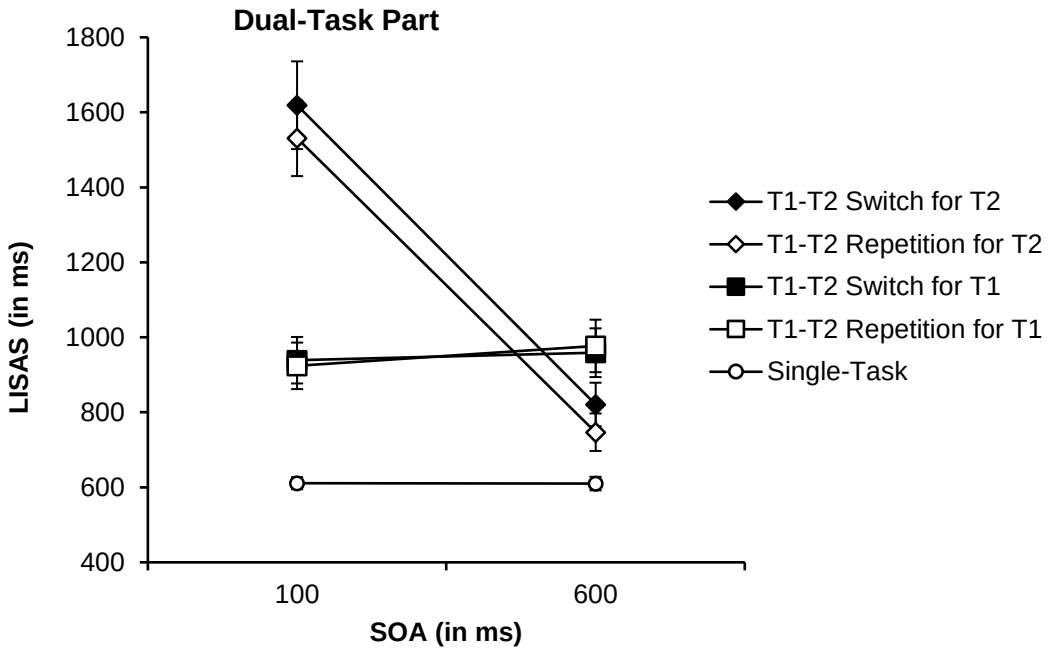

Figure 2. LISAS (in ms) in the dual-task part as a function of trial type (T1-T2 switch trials, T1-T2 repetition trials, and single-task trials) and stimulus onset asynchrony (SOA; 100 ms vs. 600 ms). Error bars represent the standard error.

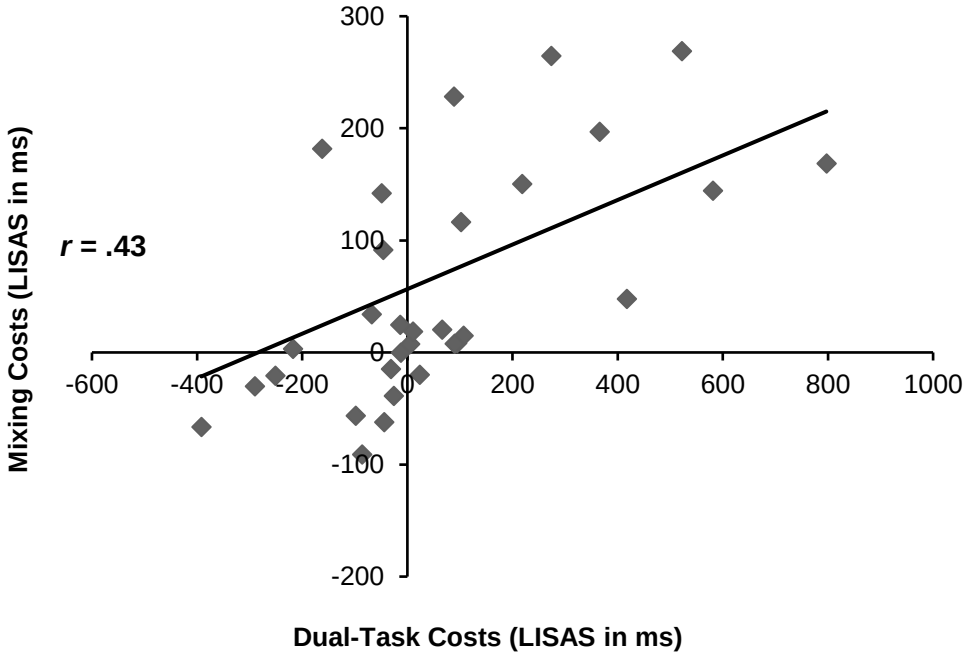

Figure 3. Correlation between mixing costs and dual-task costs (i.e., only for long SOA).

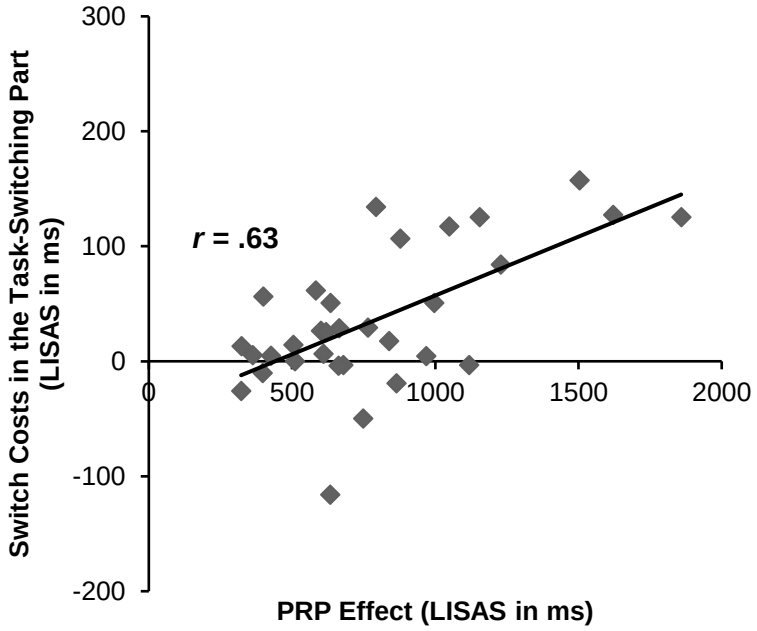

Figure 4. Correlation between switch costs and the PRP effect.

Appendix

Table 1

A. Task-switching part: Mean RTs and error rates as a function of trial type (switch, repetition, vs. single-task) and response-stimulus interval (RSI; 100 ms vs. 600 ms). B. Dual-task part: Mean RTs and error rates as a function of trial type (T1-T2 switch, T1-T2 repetition, vs. single-task) and stimulus-onset asynchrony (SOA; 100 ms vs. 600 ms) for T1 and T2.

	RT			**Error rates**		
A. Task-switching	**RSI 100 ms**	**RSI 600 ms**	**RSI effect**	**RSI 100 ms**	**RSI 600 ms**	**RSI effect**
Switch	824 (37)	737 (38)	87	4.8 (0.7)	4.9 (0.6)	-0.1
Repetition	798 (32)	687 (27)	111	3.4 (0.6)	5.9 (0.8)	-2.5
Single-task	731 (21)	636 (21)	95	4.4 (1.0)	5.3 (0.9)	-0.9
Switch costs	26	50		1.4	-1.0	
Mixing costs	67	51		-1.0	0.6	
B. Dual-tasking	**SOA 100 ms**	**SOA 600 ms**	**SOA effect**	**SOA 100 ms**	**SOA 600 ms**	**SOA effect**
T1						
T1-T2 switch	887 (57)	880 (58)	7	4.7 (0.6)	7.1 (0.8)	-2.4
T1-T2 repetition	872 (56)	891 (63)	-19	4.6 (0.7)	7.9 (1.0)	-3.3
Switch costs for T1	15	-11		0.1	-0.8	
T2						
T1-T2 switch	1470 (98)	648 (44)	822	7.7 (1.1)	9.3 (1.0)	-1.6
T1-T2 repetition	1395 (87)	588 (35)	807	7.4 (1.1)	8.8 (1.2)	-1.4
Single-task	552 (10)	521 (10)	31	3.2 (0.5)	4.6 (0.6)	-1.4
Switch costs for T2	75	60		0.3	.06	
Dual-task costs	843	67		4.1	4.2	

Note. In the task-switching part, there were speed-accuracy trade-offs with regard to the main effect of RSI (mixing-cost contrast: RSI effect of 103 ms in the RT data, $F(1, 31) = 116.24$, $p < .001$, $\eta_p^2 = .79$, and reversed RSI effect of -1.7% in the error data, $F(1, 31) = 21.93$, $p < .001$, $\eta_p^2 = .41$; switch-cost contrast: RSI effect of 99 ms in the RT data, $F(1, 31) = 66.43$, $p < .001$, $\eta_p^2 = .68$, and reversed RSI effect of -1.3% in the error data, $F(1, 31) = 8.06$, $p < .01$, $\eta_p^2 = .21$,),

and the interaction of RSI and trial type (switch-cost contrast: switch costs of 26 ms with short RSI and switch costs of 50 ms with long RSI in the RT data, $F(1, 31) = 4.30$, $p < .05$, $\eta_p^2 = .12$, and switch costs of 1.4% with short RSI and switch costs of -1.0% with long RSI in the error data, $F(1, 31) = 10.31$, $p < .01$, $\eta_p^2 = .25$. In the dual-task part, there was a speed-accuracy trade-off in T2 with respect to the main effect of SOA (PRP effect of 815 ms in the RT data, $F(1, 31) = 152.96$, $p < .001$, $\eta_p^2 = .83$, and a reversed PRP effect of -1.5% in the error data, $F(1, 31) = 5.87$, $p < .05$, $\eta_p^2 = .16$).

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Hierarchical task organization in dual tasks:
Evidence for higher-level task representations

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Abstract

To examine whether hierarchical higher level task representations comprising the task sets of Task 1 (T1) and Task 2 (T2) are activated within each trial in dual task situations, we combined the psychological refractory period (PRP) paradigm with the task-pair switching logic (Hirsch, Nolden, & Koch, 2017). In Experiment 1, in which subjects switched between task-pairs including a varying T1 and a constant T2, we found a PRP effect (i.e., worse performance with short stimulus onset asynchrony [SOA] than with long SOA) and task-pair switch costs in T1 and T2 (impaired performance in task-pair switches compared to task-pair repetitions). However, since in Experiment 1 there were no forward and backward response-response compatibility effects that indicated interference between T1 and T2, we could not exclude that the activation of T1 persisted into the next trial despite the intervening T2, and hence, that task-pair switch costs are due to repetition-priming effects of T1 across task-pairs rather than due to persisting activation of task-pair representations. In Experiment 2, we used a modified task-pair switching logic with a constant T1 and a varying T2, and replicated task-pair switch costs under conditions that not only rule out repetition-priming effects of T1 across task-pairs as the source of task-pair switch costs but also disentangle the effects of switching task-pairs from those of switching T1. These effects were associated in previous studies using the original task-pair switching logic. Thus, the findings of the present study strongly suggest that hierarchical higher level task representations are activated during dual-task processing.

(251 words)

Keywords: hierarchical higher level tasks, dual-task processing, task-pairs, psychological refractory period

Introduction

In everyday life, we are often confronted with situations requiring us to multitask, and thus, to perform two tasks simultaneously. More recently, first evidence has emerged that the two tasks in dual-task situations are represented as a more complex task-pair, such as starting a car with the overlapping subtasks of releasing a clutch and pressing the gas pedal (Hirsch, Nolden, & Koch, 2017). The present study focuses on task organization in dual tasks and shows how the activation of such more complex task-pair representations affects the processing of the separate subtasks included in the more complex task-pair.

The PRP paradigm and the explanation of the PRP effect

Dual-task processing is often examined with the psychological refractory period (PRP) paradigm (e.g., Welford 1952). In this paradigm, two stimuli, Stimulus 1 (S1) and Stimulus 2 (S2), are presented with a varying stimulus onset asynchrony (SOA; time interval separating the onsets of S1 and S2), and both of them are linked to a separate reaction-time (RT) task, so that subjects perform two tasks, Task 1 (T1) and Task 2 (T2), in each trial. The main manipulation refers to the SOA, which defines the degree of parallel task processing.

Whereas RT for T1 (RT1) typically does not depend on the SOA, RT in T2 (RT2) is higher when the SOA is short and the processing of the two tasks temporally overlaps than when the SOA is long and there is no or little temporal overlap in task processing. This performance deterioration in T2 as a function of SOA is referred to as the PRP effect (see, e.g., Pashler, 1994, for a review).

The PRP effect is often explained on the basis of the response-selection bottleneck model (Pashler 1994) that postulates for each task three serial processing stages: the perceptual processing stage, the response-selection stage, and the motor processing stage. According to this model, responses can be selected only for one task at any given time, whereas all other combinations of the processing stages can proceed for two tasks simultaneously, resulting in a processing bottleneck at the response-selection stage.

At short SOAs, perceptual processing in both tasks starts and finishes almost simultaneously. Therefore, T2 response selection has to wait until the availability of the response-selection stage (i.e., until T1 response selection has finished), which postpones T2 processing until the response for T1 is selected. In contrast, at long SOAs, there is no postponement in T2 processing because perceptual processing for T2 can take place during the response selection stage of T1, so that T1 response selection has finished before the perceptual processing in T2. This results in reduced RTs with long SOAs than with short SOAs, and hence, in a PRP effect.

PRP studies have generally analysed T1 and T2 performance separately. For example, the duration of single processing stages of T1 and T2 was often varied and the effects on performance in both tasks were measured (see, e.g., Pashler 1994, for a review). In the present study, we refer to cognitive processing at the levels of T1 and T2 as processing at the local level of the subtask (i.e., subtask-level).

Before actually performing T1 and T2, however, some important cognitive parameters need to be determined. More specifically, the subtasks to be performed as T1 and T2 have to be specified and the order of the selected subtasks needs to be defined. We refer to cognitive processing involved in subtask identification and subtask order determination as processing at the global level, here operationalized as the task-pair level. Importantly, such processes that might affect performance at a more global level than that of T1 and T2 have hardly been considered yet (e.g., De Jong 1993; Navon & Miller 2002; Pashler 1994).

Global level of dual-task processing

First evidence for dual-task processing at a global level comes from studies investigating task-order coordination in dual-task situations (e.g., Luria & Meiran 2003, 2006; Szameitat, Lipsien, von Cramon, Sterr, & Schubert, 2006; Szameitat, Schubert, Müller, & von Cramon, 2002). These PRP studies used the order-switching logic, according to which two tasks (e.g., A and B) are combined to two subtask orders (e.g., Order 1: A → B; Order 2: B → A). The sequence of the subtask orders is varied, resulting in order repetition trials and order switch trials. In order repetition trials, the subtask order is the same as that in the preceding trial (e.g., Order 2 → Order 2), whereas in order switch trials, the subtask order differs from that in the previous trial (e.g., Order 1 → Order 2).

A typical finding with this logic is that T1 and T2 performances are worse in order switch trials than in order repetition trials, reflecting order switch costs (see also De Jong 1995). These costs are thought to indicate information activation of the subtask order (i.e., subtask order representations) during dual-task processing.

Importantly, order switch costs were found, although there was a task switch at the level of subtasks across trials in order repetition trials (e.g., subtask A then subtask B [i.e., AB] → AB), whereas in order switch trials, there was a subtask repetition across trials (e.g., BA → AB; see Table 1). Considering the well-known finding of the general task-switching domain that performance is impaired in task switches as compared to task repetitions (see, e.g., Kiesel et al. 2010, for a review), performance should have been worse in order repetition trials than in order switch trials due to the task switch at the local level of subtasks.

Further evidence for dual-task processing at a more global level than that of T1 and T2 comes from a study by Hirsch and colleagues (2017), who examined hierarchical task organization in dual-tasks (for hierarchical task organization in task switching, see Lien & Ruthruff 2004; Schneider & Logan 2006). More specifically, they addressed the question of whether T1 and T2 are represented as a more complex task-pair by developing a new empirical approach, called the task-pair switching logic, and implementing it into the PRP paradigm.

According to this logic, T1 varies across task-pairs (i.e., PRP trials), whereas T2 is constant across task-pairs. When employing three different tasks (e.g., A, B, and C), the tasks can be combined to two task-pairs (e.g., Task-Pair 1: AC; Task-Pair 2: BC). The sequence of the task-pairs is manipulated, resulting in task-pair repetition trials and task-pair switch trials. In task-pair repetition trials, the task-pair equals that in the previous trial (e.g., Task-Pair 2 → Task-Pair 2), whereas in task-pair switch trials, the task-pair differs from that in the preceding trial (e.g., Task-Pair 1 → Task-Pair 2; see Table 1).

Importantly, since T2 is constant across task-pairs, there is a task switch at the local level of subtasks both in task-pair repetition trials (e.g., BC → BC) and in task-pair switch trials (e.g., AC → BC). Hence, the task-pair switching logic disentangles the costs of switching at the local level of subtasks from the costs of switching at the global level of task-pairs, which were confounded in the prior studies on task-order coordination in dual-tasks.

---- Table 1----

Using this logic, Hirsch and colleagues (2017) found task-pair switch costs in T1 and T2, reflecting impaired performance in task-pair switch trials as compared to task-pair repetition trials. Thus, dual-task performance depended on the task-pair performed in the previous trial. When the task-pair in a current trial differed from that in the preceding trial, performance was worse than when the task-pair in a given trial was the same as that in the previous trial.

According to the authors, these costs indicate that information about task-pairs was activated in the previous trial and that participants adopted a representation of the specific task-pair performed in the preceding trial. Thus, subjects did not perform two separate tasks but performed a more complex task-pair in each trial. The authors referred to this more complex task-pair as hierarchical higher level task because it was superordinate to the separate subtasks. Moreover, they argued that the representation of such hierarchical higher level tasks comprise, in addition to the subtask specific task sets, higher order connections between the task sets of both subtasks (see discussion section for reflections on the organization of higher level task representations).

Pointing to the response-selection bottleneck model, which suggests that task-pair switch costs in T2 might propagate from T1 to T2 and would, therefore, not reflect costs that arise in T2 itself due to switching task-pairs, Hirsch and colleagues (2017) proposed using task-pair switch costs in T1 as an index of the activation of higher level task representations. Response selection in T1 is slowed down in task-pair switch trials due to the retrieval of a new task set for T1. Therefore, T2 processing has to wait longer for the availability of the response-selection bottleneck in task pair switch trials than in task-pair repetition trials, which explains the T2 performance difference between these two trial types, and hence, task-pair switch costs in T2.

However, since in the study by Hirsch et al. (2017), task pair switches were accompanied by a change in T1 (e.g., AC → BC), whereas task-pair repetitions came along with a repetition of T1 (e.g., BC → BC), an alternative explanation for task-pair switch costs in T1 might be that the activation of T1 persisted into the next trial despite the intervening T2. This persisting activation of T1 would enhance performance in task-pair repetition trials, where the same T1 as in the previous trial is performed. It would also hamper performance in task-pair switch trials, where another T1 is performed than that in the preceding trial. Task pair switch costs in T1 would then result from repetition priming effects of T1 rather than from switching task-pair representations.

An analysis of forward and backward R-R compatibility effects (e.g., Fischer & Dreisbach 2015; Hommel 1998; Miller 2006; Schuch & Koch 2004) provided evidence against this alternative account. R-R compatibility effects reflect worse performance with incompatible R-R relations than with compatible ones. The R-R relation is compatible, when the responses for two tasks share common features (e.g., left key of a set of two keys for T1 and left key of another set of two keys for T2) and when they do not, the relationship is incompatible. R-R compatibility effects in T2 are referred to as forward R-R compatibility effects, whereas those in T1 are termed backward R-R compatibility effects. Both types of R-R compatibility effects are seen as providing an indication for between-task interference (e.g., Heuer 1991).

Between-task interference is affected by factors such as the stimulus valence and the response valence. Whereas univalent stimuli comprise features that are relevant for one task only, bivalent stimuli contain features that are relevant for two tasks, resulting in competing task sets, and hence, in increased interference between tasks. Between-task interference is also increased when responses for two tasks overlap physically (i.e., same response keys for both tasks) or conceptually (i.e., one set of response keys for each task with the same spatial mapping). When there is no overlap in the response specifications of the tasks, the responses

are univalent and the competition between the response sets is low. Gade and Koch (2007) demonstrated that between-task interference caused by response-set overlap is reduced by inhibiting the previous task set (see Koch, Gade, Schuch, & Philipp, 2010, for a review about inhibition in task-switching).

Hirsch et al. (2017) used univalent stimuli and conceptually overlapping responses and showed that there was considerable interference between T1 and T2 in their study, as indicated by R-R compatibility effects. By referring to the findings by Gade and Koch (2007), they argued that, due to the interference between T1 and T2, subjects were forced to reduce the activation of T1 during T2 processing, so that repetition-priming effects of T1 could not account for the observed task-pair switch costs in their study.

Finally, Hirsch and colleagues (2017) examined the source of task-pair switch costs. Using the *n*-2 repetition paradigm (Mayr & Keele 2000), they looked at the selection mechanisms acting at the global level of task-pairs. When inhibitory processes regulate the task-pair activation levels, then performance in *n*-2 task-pair repetition trials (e.g., Task-Pair 3 → Task-Pair 2 → Task-Pair 3) should be worse than in *n*-2 task-pair switch trials (e.g., Task-Pair 1 → Task-Pair 2 → Task-Pair 3), resulting in *n*-2 task-pair repetition costs. This is because, in *n*-2 task-pair repetition trials, subjects have to overcome the inhibition elicited to the task-pair in trial *n*-1, leading to impaired performance. In contrast, in *n*-2 task-pair switch trials, subjects do not return to a task-pair that was inhibited in the preceding trials. However, in contrast to such an inhibitory account, Hirsch et al. (2017) found *n*-2 task-pair switch costs, indicating that persisting activation, which results in residual positive priming of the previous relevant task-pair representation, is the primary source of task-pair switch costs.

In sum, Hirsch and colleagues (2017) found first evidence for the activation of task-pair representations during dual-task processing. In Experiment 1 of the present study, we aimed to replicate their findings. In Experiment 2, we then analysed the impact of the association between switching task-pairs and switching T1 on the processing at the global level of higher level tasks. We, therefore, modified their original task-pair switching.

Modification of the task-pair switching logic

To disentangle the effects of switching task-pairs from those of switching T1, we propose a modified task-pair switching logic with a constant T1 and a varying T2 that ensures that T1 is the same across task-pair switch trials and task-pair repetition trials (see Table 1). This modification allows re-assessing task-pair switch costs under conditions that exclude both the association between the effects of switching task-pairs and those of switching T1, and the

alternative account of repetition-priming effects of T1 across trials as the source of task-pair switch costs.

When using this modification, repetition-priming effects of T1 across task-pairs can no longer explain the existence of task-pair switch costs in T1, because, due to the constant T1, these priming effects would occur in task-pair switch trials as well as in task-pair repetition trials and would thus affect T1 performance in both trial types. Repetition priming effects of T2 across task-pairs cannot account for task-pair switch costs in T1, too, because a repetition of T2 across task-pairs should have no impact on the processing of the constant T1.

Hence, task-pair switch costs measured with this modified logic provide clearer evidence for the activation of higher level task representations in dual-task situations than the costs assessed with the original task-pair switching logic (Hirsch et al. 2017). The modified logic does not only rule out the association between the effects of switching task-pairs and those of switching T1 and repetition-priming effects of T1 across trials as an alternative account for task-pair switch costs, but it also makes the assessment of these costs independent of between-task interference, and hence, of the stimulus and response valence.

The present study

In the present study, we report two experiments which showed that hierarchical higher level task representations are activated in dual-task situations. Hirsch and colleagues (2017) already found first evidence for the activation of such higher level task representations. Since they were interested in inhibitory processes at the global level of dual-task processing, they used three task-pairs in all of their experiments. In the following study, we wished to follow-up on the earlier findings to extend the findings of Hirsch et al. (2017) with respect to two tasks, and hence, to less complex experimental settings. This was the purpose of Experiment 1 in which we combined the original task-pair switching logic with two task-pairs. However, in Experiment 2, we go beyond that earlier study by employing the modified task-pair switching logic to show that task-pair switch costs occur even when T1 is the same across task-pair switch trials and task-pair repetition trials, and hence, that neither repetition-priming effects of T1 across trials nor the association between switching T1 and switching task-pairs cause task-pair switch costs.

Experiment 1

The goal of Experiment 1 was to replicate and to generalize the findings by Hirsch and colleagues (2017) to less complex experimental situations by combing the original task-pair switching logic with two task-pairs. At the local level of dual-task processing, we assumed to find a PRP effect and R-R compatibility effects, indicating between-task interference. At the

global level of dual-task processing, we hypothesized to observe task-pair switch costs in T1 and T2. These costs would suggest that higher level task-pair representations are also activated when subjects switch only between two task-pairs.

Method

Participants. Twenty-four subjects (23 women; 18 right-handed; *M* = 22.0 years; *SD* = 3.2) participated in the experiment and received partial course credit. The participants had normal or corrected-to-normal vision and no hearing impairments.

Stimuli, tasks, and responses. The stimuli, tasks, and responses were adopted from Hirsch and colleagues (2017; Experiment 1).We used three task cues, comprising the German words for side, orientation, and object (*Seite, Orientierung*, and *Objekt*), a fixation cross, and eight pictures (7 cm × 6 cm; S1) as visual stimuli which appeared in the centre of a white 17-inch screen. The cues and the fixation cross were presented in 28-point, black Arial font. The pictures showed either a black can or a black cup, with upright or upside-down orientation, and with a handle on the left or the right side of the object. As auditory stimuli, we used two tones (200 and 600 Hz; S2).

T1 was defined by the task cue. The cue *side* required the participants to decide whether the handle was on the left or the right side of the object. The cue *orientation* introduced the subjects to make a decision about whether the object was presented upright or upside down. The cue *object* required the subjects to decide whether the object was a can or a cup. To S1 participants responded with the middle finger and the index finger of the left hand by pressing the *Y* or *X* key of a keyboard. Due to the spatial stimulus-response compatibility effect (e.g., Fitts & Deininger, 1954; Fitts & Seeger, 1953), participants responded with the *Y* key to objects with a handle on the left side and with the *X* key to objects with a handle on the right side. For the orientation task and the object task, we counterbalanced the stimulus-response mapping across subjects.

In T2, participants were asked to decide whether a tone was low or high in pitch. Taking into account the spatial-musical association of response codes effect (e.g., Keller & Koch 2006, 2008; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006), they responded to low-pitch tones with the *N* key and to high pitch tones with the *M* key. Responses were entered with the index finger and the middle finger of the right hand.

Each of the visual tasks was combined with the auditory task, resulting in three task-pairs: Task-Pair 1 with the side task as T1, Task-Pair 2 with the orientation task as T1, and Task-Pair 3 with the object task as T1. In all task-pairs, T2 was the auditory task. Unlike the

study by Hirsch et al. (2017), in the present study each participant performed only two of the three task-pairs (counterbalanced across participants).

Procedure. The participants were tested individually in a single session. The instructions appeared on the screen at the beginning of the experiment and emphasized speed and accuracy for both tasks. The participants performed first a practice block of 12 trials, followed by 5 experimental blocks, each comprising 65 trials.

The trial procedure was similar to that used by Hirsch and colleagues (2017). Each trial started with the display of a task cue. After 400 ms, the cue was replaced by a fixation cross that was presented for further 100 ms, resulting in a cue stimulus interval (CSI) of 500 ms. After the CSI, S1 appeared for 100 ms. S2 was presented after an SOA of 50 or 800 ms for 100 ms. The next task cue was displayed 1000 ms after the response to S2 was executed. The sequence of the task-pairs was random with the restriction of a balanced number of task-pair switches with a short SOA, task-pair switches with a long SOA, task-pair repetitions with a short SOA, and task-pair repetitions with a long SOA within the experimental blocks.

Design. T1 and T2 performances were analysed based on a 2 × 2 × 2 repeated-measures design with the within-subject independent variables task-pair sequence (task-pair switch vs. task-pair repetition), SOA (50 ms vs. 800 ms), and R-R compatibility (incompatible vs. compatible). The dependent variables were RT and error rates.

Results and discussion

Separate analyses of variance (ANOVAs) were run on mean RTs and error rates (see Figure 1 and Table 2). We excluded practice trials and the first trial in each experimental block from all analyses. As outliers, we defined trials with RTs exceeding 3 *SD* from a given participant's mean (T1: 1.3%; T2: 1.4%). In the RT analysis, only trials with correct responses in T1 and T2 that were preceded by a correct trial were included.

----Figure 1 and Table 2----

T1. The ANOVA on RT1 showed the expected main effect of task-pair sequence, $F(1, 23) = 6.39$, $p < .05$, $\eta_p^2 = .22$. The participants responded more slowly in task-pair switch trials than in task-pair repetition trials (731 ms vs. 700 ms; task-pair switch costs: 31 ms). All other effects were non-significant, all *p*s > .29.

For the accuracy data, a trend was observed towards larger task-pair switch costs in R-R incompatible trials than in R-R compatible trials (2.3% vs. 0%). However, the interaction of task-pair sequence and R-R compatibility was not significant, $F(1, 23) = 3.05$, $p = .09$, $\eta_p^2 = 0.12$, like all other effects, all *p*s > 0.13. Post hoc one-tailed *t*-tests showed that task-pair switch costs were significant with incompatible R-R relations, $t(23) = 2.18$, $p < .05$, $d = 0.42$, and non-

significant with compatible R-R relations, $t(23) = 0.02$, $p = .50$, $d = 0.01$. At the same time, however, the trend showed that in task-pair switch trials, there was a typical backward R-R compatibility effect with more erroneous responses in R-R incompatible trials than in R-R compatible trials (8.2% vs. 6.2%; post hoc two-tailed *t*-tests: $t(23) = 2.42$, $p < .05$, $d = 0.34$), whereas in task-pair repetition trials, there was a reversed backward R-R compatibility effect with more error prone responses in R-R compatible trials than in R-R incompatible trials (6.2% vs. 5.9%; post hoc two-tailed *t*-tests: $t(23) = -0.30$, $p = .76$, $d = -0.05$).

T2. For RT2, there was a significant main effect of task-pair sequence, $F(1, 23) = 7.70$, $p < .05$, $\eta_p^2 = .25$, indicating task-pair switch costs of 44 ms (task-pair switches: 964 ms; task-pair repetitions: 920 ms). Moreover, the main effect of SOA was significant, $F(1, 23) = 966.26$, $p < .001$, $\eta_p^2 = .98$. Responses in T2 were slower after a short SOA than a long SOA (1229 ms vs. 655 ms), reflecting a PRP effect of 574 ms. All other effects were non-significant, all *p*s > .28.

For the accuracy data, the ANOVA also yielded a main effect of SOA, $F(1, 23) = 4.99$, $p < .05$, $\eta_p^2 = .18$. There were more error-prone responses after a short SOA than a long SOA (7.1% vs. 5.7%; PRP effect: 1.4%). All other effects were not significant, all *p*s > 0.10.

At the local level of dual-task processing, we observed a PRP effect, which indicated performance deteriorations due to overlapping task processing. At the global level of dual-task processing, there were task-pair switch costs. However, since there were no R-R compatibility effects indicating interference between T1 and T2, we could not ensure that the activation of the task set in T1 persisted into the next dual-task trial where it enhanced performance in task-pair repetition trials. To rule out such repetition-priming effects across task-pairs as the source of task-pair switch costs, we ran Experiment 2.

Experiment 2

In Experiment 1, we replicated task-pair switch costs with two task-pairs. However, unlike Hirsch and colleagues (2017), we found no R-R compatibility effects in Experiment 1 that would indicate that there was between-task interference, and hence, that subjects were forced to reduce T1 activation during T2 processing (see Gade & Koch 2007). Thus, we could not exclude repetition-priming effects of T1 across dual-task trials as the source of the task-pair switch costs observed in Experiment 1. To ensure that task-pair switch costs were not due to the persisting activation of T1 across trials, we ran Experiment 2 where we used the modified task-pair switching logic. Since in the context of this logic T1 is constant across task-pair switch trials and task-pair repetition trials, the logic not only disentangles the effects of switching task-

pairs from those of switching T1, but also rules out repetition-priming effects of T1 across trials as an alternative account for these costs.

By changing the order of the varying visual T1 and the constant auditory T2 used in Experiment 1, we implemented the modified task-pair switching logic into Experiment 2 to find clearer evidence for the activation of higher order tasks during dual-task processing. Again, we assumed to find a PRP effect and task-pair switch costs.

Method

Participants. A new group of 24 subjects (20 women; 21 right-handed; *M* = 23.5 years; *SD* = 2.4) participated in Experiment 2. All participants had normal, or correct-to-normal, vision and intact auditory skills.

Stimuli, tasks, responses, and procedure. The stimuli, the tasks, and the procedure were identical to those used in Experiment 1. However, as opposed to Experiment 1, we used the auditory task as constant T1 and the visual task as varying T2.

Design. T1 and T2 performance was analysed based on a 2 × 2 repeated-measures design with the independent within-subject variables task-pair sequence (task-pair switch vs. task-pair repetition) and SOA (50 ms vs. 800 ms). Since repetition-priming effects of T1 across trials could not account for task-pair switch costs due to the constant T1, the analysis of the R-R compatibility effect as an indication for between-task interference was not necessary.

Results and discussion

Using the same outlier criteria as in Experiment 1, we excluded 1.1% outliers in T1 and 1.0% in T2 and ran separate ANOVAs on mean RTs and error rates (see Figure 2 and Table 2).

----Figure 2----

T1. For RT1, there was a main effect of task-pair sequence, $F(1, 23) = 29.25$, $p < .001$, $\eta_p^2 = .65$, indicating that RT was higher in task-pair switch trials than in task-pair repetition trials (1214 ms vs. 1095 ms; task-pair switch costs: 119 ms). Moreover, descriptively, there was a trend towards slower responses in trials with a long SOA than in trials with a short SOA (1201 ms vs. 1109 ms). However, this numerically large effect of 92 ms was not significant, $F(1, 23) = 4.04$, $p = .056$, $\eta_p^2 = .15$. All other effects in the RT data and the accuracy data were non-significant, too, all *p*s >.20.

T2. The ANOVA on RT2 showed a significant main effect of task-pair sequence, $F(1, 23) = 33.57$, $p < .001$, $\eta_p^2 = .59$, and SOA, $F(1, 23) = 116.21$, $p < .001$, $\eta_p^2 = .84$, reflecting higher RT2 in task-pair switch trials than in task-pair repetition trials (1513 ms vs. 1329 ms; task-pair switch costs: 184 ms) and in trials with a short SOA than in trials with a long SOA

(1663 ms vs. 1179 ms; PRP effect: 484 ms). The interaction of SOA and task-pair sequence was non-significant, $F < 1$.

For the accuracy data, the main effects of task-pair sequence, $F(1, 23) = 20.01$, $p < .001$, $\eta_p^2 = 0.47$, and SOA, $F(1, 23) = 11.90$, $p < .01$, $\eta_p^2 = .34$, were also significant. There were more erroneous responses in task-pair switch trials than in task-pair repetition trials (12.5% vs. 9.2%; task-pair switch costs: 3.3%) and in trials with a short SOA than in trials with a long SOA (11.8% vs. 9.9%; PRP effect: 1.9%). The interaction of task-pair sequence and SOA was not significant, $F < 1$.

Besides the PRP effect, we replicated task-pair switch costs with a constant T1 and a varying T2. The existence of task-pair switch costs in an experimental setting with a constant T1 provides clearer evidence for the activation of higher level task representations in dual-task situations because neither the association between switching task-pairs and switching T1 nor the repetition-priming effects of T1 from one trial to the next can account for these costs.

Interestingly, the RTs and task-pair switch costs revealed in Experiment 2 were more pronounced than those in Experiment 1 (RT1: 1155 ms vs. 715 ms; RT2: 1421 ms vs. 941 ms; costs in T1: 120 ms vs. 31 ms; costs in T2: 184 ms vs. 44 ms). The higher RTs in Experiment 2 might be due to a general increase in the processing time required for auditory tasks or/and due to the fact that subjects had to maintain in working memory the task-pair cue that defines the identity of T2, during T1 processing. The maintenance of the task-pair cue during T1 processing seems also to hamper task-pair switching, resulting in higher task-pair switch costs. However, since the experiments were not fully comparable, the impaired performance in Experiment 2 relative to Experiment 1 is hard to interpret. To compare performance measured with the original task-pair switching logic to that assessed with the modified logic, it would be advisable to ensure that the modality of T1 and T2 is the same for both types of the task-pair switching logic.

General discussion

The aim of the present study was to find further evidence for the activation of higher level task representations covering the task sets of T1 and T2 by rendering the findings of task-pair switch costs into less complex dual-task situations, and more importantly, by replicating these costs under improved methodological conditions that exclude the alternative explanations that task-pair switch costs are due to the association between switching task-pairs and switching T1, or due to repetition-priming effects of T1 across task-pairs. To this end, we used the original task-pair switching logic with a varying T1 and a constant T2 in Experiment 1, and modified this logic using a constant T1 and a varying T2 in Experiment 2. In Experiment 1, we observed

a PRP effect and task-pair switch costs but no R-R compatibility effects. In Experiment 2, we replicated the PRP effect and task-pair switch costs with a constant T1.

Processing at the local level of subtasks

In line with the findings about processing at the local level of subtasks, we found T2 performance to be impaired with short SOA as compared to long SOA, reflecting a PRP effect (see, e.g., Pashler 1994, for a review). This suggests that overlapping task processing impairs T2 performance. Whereas in Experiment 1, T1 performance was unaffected by the SOA, in Experiment 2, RT1 was slower with long SOA than with short SOA, possibly indicating response grouping (Ulrich & Miller 2008)[1]. However, this effect was not significant.

Moreover, neither T1 nor T2 performance was influenced by the R-R compatibility, as indicated by the absence of forward and backward R-R compatibility effects. Hirsch et al. (2017), who ran experiments with the same stimuli, tasks, and responses, found forward and backward R-R compatibility effects, revealing considerable interference between T1 and T2.

However, in their study, subjects switched between three competing task-pairs. This suggests that in the context of two task-pairs in the present Experiment 1, conceptual response-set overlap does not instigate sufficient interference between T1 and T2, and thus, that the activation of T1 does not have to be necessarily reduced during T2 processing.

Processing at the global level of task-pairs

In task-pair switch trials, where the task-pair differed from that presented in the preceding trial, performance was worse than in task-pair repetition trials, where the same task-pair was displayed as in the previous trial. This suggests that subjects adopted a representation of the specific task-pair performed in the previous trial and that this representation was still active to some degree in the next trial. When subjects had to perform another task-pair in the next trial, a reconfiguration of the task-pair representation, a readjustment of its activation, or both was necessary, resulting in task-pair switch costs (see Allport, Styles, & Hsieh, 1994; Rogers & Monsell 1995, for corresponding accounts in task switching).

In Experiment 1, where subjects switched between two task-pairs with a varying T1 and a constant T2, task-pair switch costs represent a replication of the findings by Hirsch et al. (2017) and show that these costs are a general phenomenon which is not restricted to dual-task situations with three task-pairs. However, an alternative account for the task-pair switch costs observed with the original task-pair switching logic might be that the activation of the task set of T1 persists into the next trial despite the intervening T2. This persisting activation would enhance performance in task-pair repetition trials and hamper performance in task-pair switch trials. In Experiment 1, this alternative account could not be ruled out by the existence of

forward and backward R-R compatibility effects, which would confirm strong interference between T1 and T2 which is thought to force subjects to inhibit the activation of T1 when performing T2 (Gade & Koch 2007).

To exclude the repetition-priming effects of T1 across trials and the association between switching task-pairs and switching T1 as source of task-pair switch costs, we employed in Experiment 2 the modified task-pair switching logic which ensures that T1 is the same across task-pair switch trials and task-pair repetition trials. Using this modified logic, we replicated task-pair switch costs in T1 and T2.

The task-pair switch costs observed in Experiment 2 provide clear evidence that subjects adopted a representation of the specific task-pair performed in the previous trial, reinforcing the findings of Experiment 1. These representations can be seen as indication that subjects executed a more complex task-pair including T1 and T2 as subtasks. Following Hirsch and colleagues (2017), we refer to this more complex task-pair as a hierarchical higher level task that was superordinate to the separate subtasks performed at each trial.

We assume that hierarchical higher level task representations include, in addition to subtask-relevant information, all cognitive parameters that enable participants to identify the relevant subtasks for a task-pair and possibly also to perform them in a proper order. Since subtask identity and serial position codes have to be available before performing one of the subtasks, cognitive parameters related to separate subtasks (e.g., S-R mappings) might be organized at a hierarchically lower level than those concerning the task-pairs themselves. Hence, the hierarchy within the higher level task representation might be defined by a temporal precedence of specific processes.

In cognitive psychology, there has been much debate concerning the organization of task sets. Aside from the consensus that a task set is a temporary representation that includes all relevant information to perform a task, there are different views on what type of information is contained in a task set and how information is organized within a task set (Vandierendonck, Christiaens, & Liefooghe, 2008).

Different views on the task-set organization have been proposed and empirically underpinned—especially using the two-component task-switching procedure. With this procedure, in addition to the task itself, a further task component (e.g., response modality) can switch or repeat between two successive trials so that the performance between one-component switches and two-component switches can be compared (e.g., Hahn, Andersen, & Kramer, 2003; Hübner, Futterer, & Steinhauser, 2001). This approach led to the development of three

different views on the task-set organization: flat organization, hierarchical organization, and componential organization.

In a flat organization, all task-set components are supposed to be integrated into one single representation, and within this representation 'all task-set components play the same role for the cognitive representation of the task, so that a change in either one or both components results in a new task set' (Philipp & Koch 2010, p. 386; see also; Vandierendonck et al., 2008). In a hierarchical organization, task-set components are also assumed to be integrated but to be organized hierarchically with different components at superordinate and subordinate levels (e.g., Kleinsorge 2004; Kleinsorge & Heuer, 1999; Kleinsorge, Heuer, & Schmidtke, 2001, 2004). It is assumed that a switch at the superordinate level (e.g., the stimulus categorization) also results in switches at the subordinate level (e.g., the specific S-R mapping). When only a switch at the superordinate level is required, the subordinate task-set component must be switched back, resulting in additional costs. In a componential organization, task-set components are uncoupled and independent of each other, so that each change of a component leads to a cost (e.g., Hübner et al., 2001; Rangelov, Töllner, Müller, & Zehetleitner, 2013). Since the present study does not allow a distinction between one and two-component switches, we are not able to conclude whether T1 and T2 are organized in a flat, hierarchical, or componential representation.

A further important question refers to the point in time at which higher level task representations are available. Statistical analysis showed that task-pair switch costs did not differ in size depending on whether the SOA from the previous trial was repeated or switched[2]. This indicates that the specific duration of the SOA performed in the previous trial is not a part of hierarchical higher level task representations and hence that temporal information on the onset of T2 is not included in these representations. This observation speaks against the possibility that higher level task representations are only available after performing a task-pair. In this case, the specific SOA of the previous trial should be part of the representation. The observation that the specific SOA level of the previous trial is not included in higher level task representations might indicate that these representations were activated by the cue. Since the SOA was not available at this point of time, the SOA is not a part of the representation.

In the present study, a cue announced the task-pair at the beginning of each trial. Since there was one cue per task-pair, the task-pair sequence was associated with the cue sequence. Hence, the observed task-pair switch costs are composed of cue-switching effects and task-pair switching effects of unknown size. Previous research showed that both switching cues and switching tasks result in substantial performance costs (e.g., Altmann, 2006; Arrington, Logan,

& Schneider, 2007; Jost, Mayr, & Rösler, 2008; Monsell & Mizon 2006). In line with these findings, we assume that a part of the total task-pair switch costs measured in the present study could be attributed to cue switching, but task-pair switching per se produces an additional cost that cannot be explained by cue switching itself.

More specifically, we argue that cues were translated into higher level task representations that enable subjects to select and perform the relevant subtasks in the proper order. Hence, the cue was used to establish relevant representations of the task-pair in working memory. The translation proceeded fast when the corresponding higher level task representation was still activated to some degree owing to its relevance in the previous trials and even faster when the cue was primed in working memory. Previous research has shown task switch costs, observed with the explicit cueing procedure, to not be solely due to perceptual priming of the cue itself and, therefore, we assume that the measured task-pair switch costs in the present study provide evidence for task-pair switching-related costs. However, to determine the relative contributions of cue switching as well as task-pair switching to task-pair switch costs, additional research with two cues per task is necessary.

The idea of higher level task representations is also compatible with the notion of event files in which relevant aspects of a task are bound together (see, e.g., Hommel 2004; Logan 1988). However, in contrast to a binding between stimuli and responses in a single task, higher level task representations assume a higher level event file which includes two tasks and their order position. Thus, a task-pair could be seen as a specific task context (cf. Hommel, 2004) in which two individual tasks with local S-R bindings are integrated. In this context, future research exploring the interplay between S-R binding on a local level and higher level event files is certainly of interest.

Conclusion

By ruling out two alternative explanations for task-pair switch costs and replicating these costs in the context of two task-pairs, we concluded that these costs represent a robust effect that is not limited to the number of task-pairs subjects had to switch between and that these costs represent a valid index for the activation of hierarchical higher level task representations covering the task sets of T1 and T2.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest (financial or non-financial). Moreover, we have full control of all primary data and we agree to allow the journal to review the data if requested.

Ethical approval All procedures performed in the present study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standard.

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Footnotes

[1] To examine whether this trend was due to response grouping, we analysed inter-response intervals (IRIs; i.e., time interval between the response for T1 and for T2). We considered IRIs less than 200 ms to be indicative of response grouping (e.g., De Jong, 1993). Overall, there were 3.8% trials with IRIs less than 200 ms. Moreover, the analysis showed that one participant grouped the responses in 20.9% of the trials. The result pattern did not change if the subject who showed an extreme grouping behaviour and the trials with IRIs less than 200 ms were excluded from all analyses. However, the SOA effect on T1 was statistically smaller, $F(1, 22) = 3.23$, $p = .09$, $\eta_p^2 = .13$. In Experiment 1, we identified 0.56% trials with IRIs less than 200 ms. The result pattern did not change if these trials were discarded from all analyses.

The proportion of grouped trials was larger in Experiment 2 than in Experiment 1. The main difference between the experiments is that in Experiment 1, T1 varied and T2 remained constant across task-pairs, whereas in Experiment 2, T1 was constant and T2 varied across task-pairs. Thus, in Experiment 2, subjects had to maintain the task-pair cue during T1 processing and until the presentation of S2 in working memory, whereas in Experiment 1, the task-pair cue was already relevant for T1. The maintenance of the task-pair cue in working memory during T1 processing or until the presentation of S2 might have promoted response grouping in Experiment 2.

[2] To examine whether task-pair switch costs differ depending on whether the SOA in the previous trial was repeated or switched, we ran additional ANOVAs with the within-subjects variables task-pair sequence (task-pair switch vs. task-pair repetition) and SOA sequence (SOA switch vs. SOA repetition) for trials with a short SOA. In the following, to avoid redundancy, we report only effects including the SOA sequence variable. In Experiment 1, we exclude one participant from all analysis due to an overall error rate of < 25%. For the error rates in T2, there was a trend toward more erroneous responses in SOA repetition trials than in SOA switch trials (6.9% vs. 5.6%). However, like all other effects, all *p*s > .15, the main effect of SOA sequence was not significant, $F(1, 22) = 3.69$, $p = .07$, $\eta_p^2 = .14$. In Experiment 2, task-pair switch costs for the error rates in T2 were numerically larger in SOA switch trials than in SOA repetition trials (5.6% vs. 2.1%). However, the interaction of task-pair sequence and SOA was not significant, $F(1, 22) = 3.72$, $p = .07$, $\eta_p^2 = .14$. All other effects were non-significant, too, all *p*s >.16.

Table 1

Sequences at the global task-pair level and the local subtask level in the present study (Experiment 1 & Experiment 2) and in the studies by Luria and Meiran (2003, 2006) and by Hirsch et al. (2017).

Task-pair transition	Global task-pair switch	Local T1-T1 switch	Local T2-T1 switch
Luria & Meiran (2003, 2006)			
AB → AB	×	×	✓
BA → BA	×	×	✓
AB → BA	✓	✓	×
BA → AB	✓	✓	×
Hirsch et al. (2017) and present Experiment 1			
AC → AC	×	×	✓
BC → BC	×	×	✓
BC → AC	✓	✓	✓
AC → BC	✓	✓	✓
Present study Experiment 2			
CA → CA	×	×	✓
CB → CB	×	×	✓
CA → CB	✓	×	✓
CB → CA	✓	×	✓

Table 2

Mean error rates (in percentage; standard errors in parenthesis) in Experiment 1 (separated for incompatible and compatible response-response [R-R] relations) and Experiment 2 for Task 1 (T1) and Task 2 (T2) as a function of task-pair sequence (task-pair repetition vs. task-pair switch) and stimulus onset asynchrony (SOA; 50 ms vs. 800 ms).

	T1		T2	
	SOA 50 ms	SOA 800 ms	SOA 50 ms	SOA 800 ms
Experiment 1				
Incompatible R-R relations				
task-pair switch	8.7 (1.5)	7.7 (1.5)	6.1 (1.2)	4.6 (0.6)
task-pair repetition	6.1 (1.4)	5.7 (1.0)	6.7 (1.6)	5.5 (1.2)
task-pair switch costs	2.6	2.0	-0.6	-0.9
Compatible R-R relations				
task-pair switch	6.5 (1.6)	6.0 (1.0)	8.8 (1.5)	5.9 (1.3)
task-pair repetition	6.6 (1.2)	5.8 (1.3)	6.9 (1.4)	6.7 (1.3)
task-pair switch costs	-0.1	0.2	1.9	-0.8
Experiment 2				
task-pair switch	3.5 (0.7)	3.9 (0.7)	13.7 (1.2)	11.4 (1.5)
task-pair repetition	4.2 (0.8)	3.3 (0.5)	9.9 (1.1)	8.4 (1.0)
task-pair switch costs	-0.7	0.6	3.8	3.0

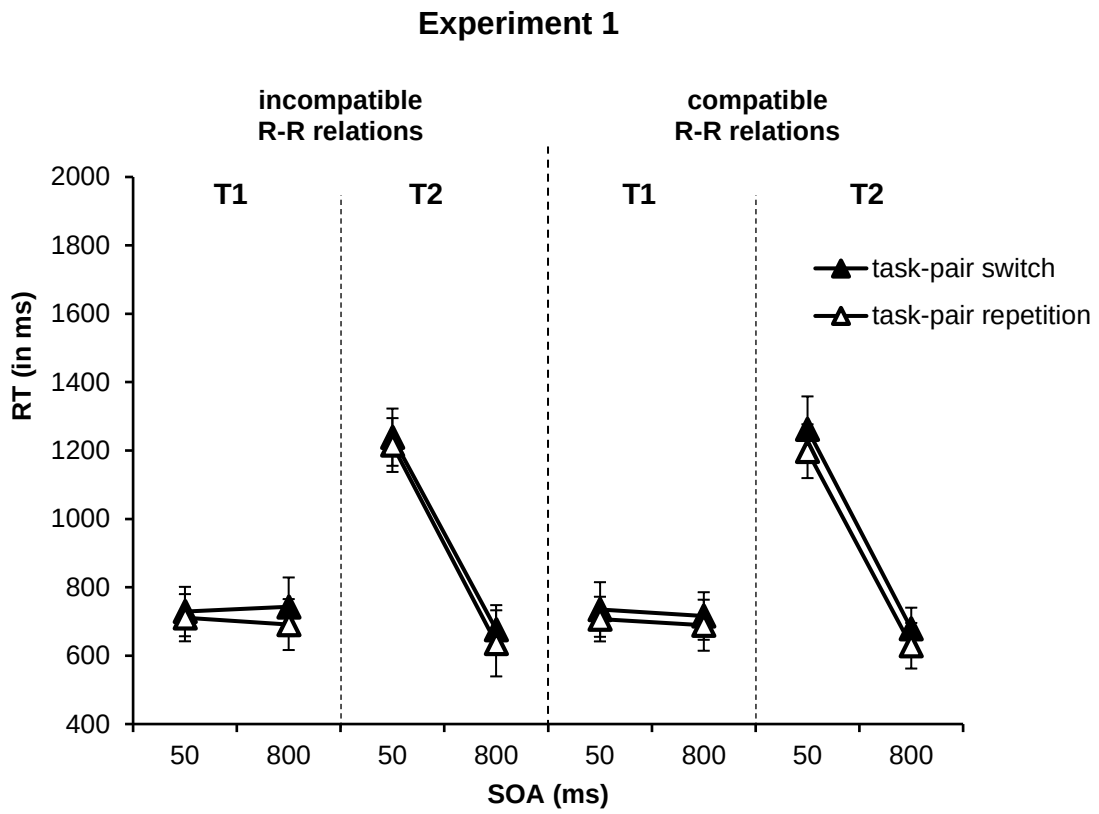

Figure 1. RT (in ms) in Experiment 1 (separated into incompatible and compatible response-response [R-R] relations) for Task 1 (T1) and Task 2 (T2) as a function of task-pair sequence (task-pair switch vs. task-pair repetition) and SOA (50 ms vs. 800 ms). Error bars represent the within-subjects error (Morey, 2008).

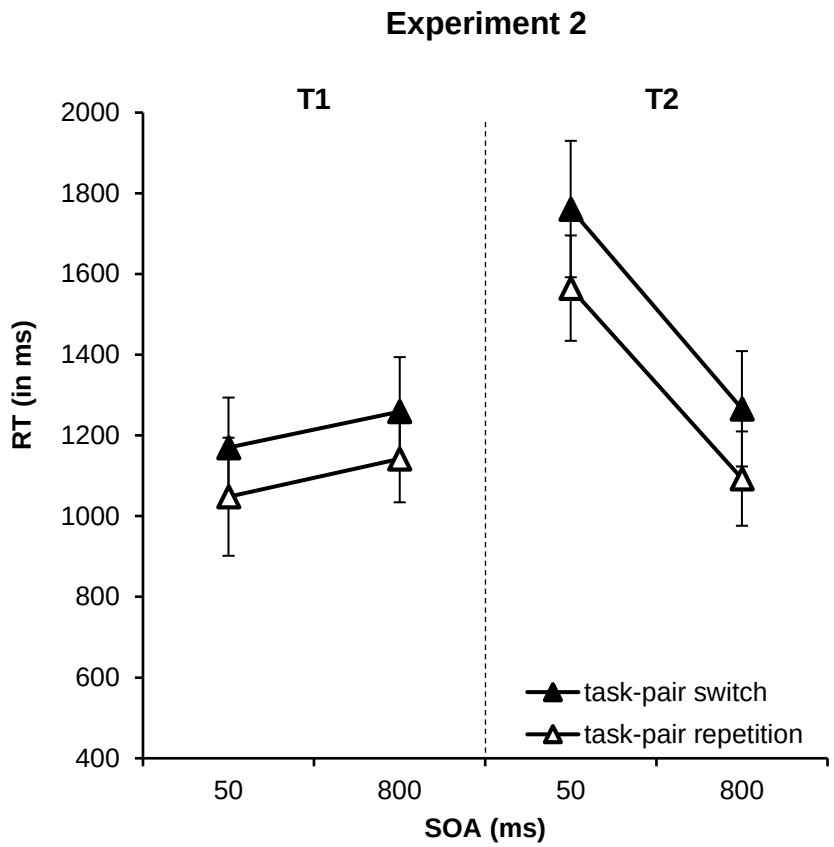

Figure 2. RT (in ms) in Experiment 2 for Task 1 (T1) and Task 2 (T2) as a function of task-pair sequence (task-pair switch vs. task-pair repetition) and SOA (50 ms vs. 800 ms). Error bars refer to the within-subjects error (Morey, 2008).

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Higher-order cognitive control in dual tasks:
Evidence from task-pair switching

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Abstract

In the present study, we combined the psychological refractory period (PRP) paradigm with a novel task-pair switching logic which enabled us to isolate performance costs occurring at the global level of task-pairs. In Experiment 1, in which we used conceptually overlapping responses for Task 1 (T1) and Task 2 (T2), we generated three task-pairs by combining one of three visual tasks (T1) with an auditory task (T2). In addition to worse performance after a short SOA than a long SOA (i.e., PRP effect), we found impaired performance in *n*-1 task-pair switches as compared to *n*-1 task-pair repetitions (i.e., *n*-1 task-pair switch costs), suggesting that task-pairs were activated during dual-task processing. In Experiment 2, we increased the interference between T1 and T2 by using physically overlapping responses and we again observed *n*-1 task-pair switch costs. To investigate whether the activation of task-pairs is adjusted by inhibitory control, we looked at the *n*-2 task-pair sequence and found performance to be better in *n*-2 task-pair repetitions than in *n*-2 task-pair switches in both experiments. This *n*-2 task-pair repetition benefit was replicated in Experiment 3 in which no immediate task-pair repetitions were included. Hence, the evidence suggests enhanced activation rather than inhibition as a crucial selection mechanism at the global level of dual-task processing.

(210 words)

Keywords: dual tasks, PRP effect, task-pairs, cognitive control, hierarchical task organization

Public Significance Statement

Our actions often consist of several subtasks that have to be, at least partly, performed simultaneously. For example, when we want to start a car, we have to perform the two partially overlapping subtasks of releasing the clutch and pressing the gas pedal. The present study provides evidence that in dual-task situations, simultaneously performed subtasks are grouped together to a single hierarchical higher-order task, representing a higher-level connection between the task sets of both subtasks. Moreover, the findings suggest that persisting activation, which results in residual positive priming of the previously relevant higher-order task, seems to be the crucial selection mechanism at the level of higher-order tasks. Hence, in addition to cognitive control mechanisms coordinating overlapping task processing at the level of subtasks, human actions in dual-task situations are enabled by cognitive control mechanisms acting at the global level of higher-order mental representations covering the task sets of both subtasks.

In everyday life, we often start performing a second task before finishing the first one, resulting in temporally overlapping task performance. Research on such staggered dual-task performance usually analyzes the two tasks separately (e.g., Huestegge, & Koch, 2009; Janczyk, Pfister, Hommel, & Kunde, 2014; Ruthruff, Pashler, & Klaassen, 2001), while not focusing on higher-level task representations and their control mechanisms. Information about this global processing level can be obtained, for example, by investigating whether the first and second tasks in dual-task situations are represented as a higher-level task, such as starting a car, which comprises the partially temporal overlapping subtasks of releasing a clutch and pressing the gas pedal. In the present study, we addressed this question by implementing a new empirical approach into a dual-task paradigm.

PRP paradigm

A commonly used experimental tool to study dual-task performance is the psychological refractory period (PRP) paradigm (e.g., Telford, 1931; Welford, 1952). In PRP experiments, two stimuli, Stimulus 1 (S1) and Stimulus 2 (S2), are presented in rapid succession within a trial. Since both stimuli require an independent response, two separate reaction-time (RT) tasks, Task 1 (T1) and Task 2 (T2), are performed more or less simultaneously within a trial. The extent of parallel task processing is manipulated by the time interval between the presentation of S1 and that of S2 (stimulus onset asynchrony, SOA).

A typical finding with this paradigm is that RT for T1 (RT1) is generally unaffected by the SOA, whereas RT for T2 (RT2) increases with shortened SOA and, thus, with increasing temporal overlap between the processing of both tasks. This performance deterioration in T2 with decreasing SOA is referred to as the PRP effect (for reviews, see Lien & Proctor, 2002; Pashler, 1994).

In the literature, there are different models about the mechanisms underlying the PRP effect. Graded capacity sharing models assume that the information-processing capacity is limited and that in dual-task situations these limited resources have to be shared among tasks (e.g., Logan & Gordon, 2001; Navon & Miller, 2002; Tombu & Jolicoeur, 2003). When the resources are primary allocated to T1, there is a slowdown in the processing speed of T2.

In addition to graded capacity sharing models, there are also models of structural limitations of the cognitive architecture, such as the response-selection bottleneck model (e.g., Pashler, 1994). This model assumes that task processing is subdivided into three main stages, including perceptual processes, response selection, and motor processes, and that response selection cannot take place simultaneously for two tasks. Thus, T2 response selection has to wait until response selection for T1 is finished. When the SOA is long, the waiting period for

the availability of the response-selection bottleneck can be used for perceptual processes in T2. In the case of a short SOA, perceptual processing finishes almost simultaneously for T1 and T2, so that the waiting period for the response-selection completion in T1 cannot be used for other cognitive processes in T2. Hence, T2 processing is postponed until the response for T1 is selected, leading to higher RT2 with short SOA than with long SOA.

Inconsistent with such a processing bottleneck, T1 performance has been shown to be influenced by the compatibility relationship between the response for T1 (R1) and that for T2 (R2; e.g., Hommel, 1998; Janczyk et al., 2014; Lien & Proctor, 2000; Lien, Schweickert, & Proctor, 2003). The response-response (R-R) relation is compatible across tasks when R1 and R2 share common features. For example, this could be the case if both tasks involve the concepts "left" or "right" and the currently required response in both tasks is linked to the concept "left" (conceptual response-set overlap: two sets of left and right keys per task), or if in both tasks the same key is pressed even with the same effectors (physical response-set overlap: identical two keys for T1 and T2).

Using such bivalent responses that overlap at the conceptual or physical level, dual-task studies showed that T1 performance was hampered when R2 was incompatible with response codes in T1, providing evidence for parallel response activation (e.g., Hommel, 1998; Lien et al., 2003). This effect is known as backward R-R compatibility effect.

T2 performance has also been shown to be hampered when the R-R relations are incompatible (e.g., Lien, McCann, Ruthruff, & Proctor, 2005; Lien & Proctor, 2000, Schuch & Koch, 2004). These performance deteriorations in T2 due to R-R incompatibility are termed forward R-R compatibility effects.

The backward and forward R-R compatibility effects indicate that there is interference between T1 and T2 at the level of response sets (e.g., Heuer, 1991). In the present study, however, we were interested in the global level of dual-task processing, more specifically, in the processing at the level of task-pair representations.

Global processing in the PRP paradigm

The existing PRP studies (see, e.g., Pashler, 1994, for a review) and accounts of the PRP effect (e.g., Pashler, 1994; Tombu & Jolicoeur, 2003) focus mainly on cognitive processing at the level of subtasks and, thus, on T1 and T2 in isolation, while cognitive processes at a global level of dual-task processing have so far been investigated less. The few studies providing evidence for global processing address the effect of subtask order on dual-task performance (e.g., Luria & Meiran, 2003, 2006).

In the studies by Luria and Meiran (2003, 2006), a differentiation is made between two subtask orders, namely Order 1 (Task A [T1] then Task B [T2]) and Order 2 (Task B [T1] then Task A [T2]), and two types of trials, namely order repetition trials and order switch trials. In order repetition trials, the subtask order is the same as in the previous trial, while in order switch trials, the subtask order differs from that in the preceding trial.

Luria and Meiran (2003, 2006) found T1 and T2 performance to be worse in order switch trials than in order repetition trials. Referring to this data pattern as order switch cost, they argued that the existence of this cost provides evidence for the activation of subtask order information in PRP trials and, hence, for the requirement of cognitive control at a more global level than that of the subtask. Order switch costs were also found in other studies, for example, in the study by De Jong (1995) who explored preparation in overlapping-task performance and in the study by Lien and Ruthruff (2004) who investigated the effect of hierarchical task organization on task switching. Further evidence suggesting the activation of subtask order information in dual tasks comes from neuroimaging studies (e.g., Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2005; Szameitat, Schubert, Müller, & von Cramon, 2002) that report different patterns of brain activity for order repetition trials and order switch trials. In order switch trials, there was an increased activation of the lateral prefrontal cortex (i.e., cortical areas along the posterior part of the left inferior frontal sulcus and the right posterior middle frontal gyrus) that might contribute to task control.

A further important finding in the study by Luria and Meiran (2003) was that subtask order modulates the PRP effect in such a way that this effect is larger in order switch trials than in order repetition trials. This suggests that the PRP effect is increased when more cognitive control is required at the global level of dual-task processing. This finding highlights the role of global processing for dual-task performance because it illustrates that order switching affects mechanisms leading to the PRP effect.

According to Luria and Meiran (2003), the activation of subtask order information is controlled by inhibitory mechanisms that reduce the activation of the non-target subtask order to prevent this irrelevant order information from hampering performance in trials that are based on the other subtask order. They assumed that the inhibition of a subtask order persists in the next trial. That is, in order switch trials, the activation of the relevant task order is reduced because this order was irrelevant in the preceding trial and, therefore, inhibited. The inhibition has to be overcome in order switch trials, resulting in increased RT and error rates relative to order repetition trials.

Isolating effects of switching at the global level of dual-task processing

In the studies by Luria and Meiran (2003, 2006), switching at the global processing level was associated with switching at the level of subtask processing. In other words, there was a task switch between T2 of trial *n*-1 (e.g., Task A [T1] then Task B [T2]) and T1 of trial *n* (e.g., Task A [T1] then Task B [T2]) in order repetition trials (see Table 1). In contrast, in order switch trials, T2 in trial *n*-1 (e.g., Task B [T1] then Task A [T2]) was repeated in T1 of trial *n* (e.g., Task A [T1] then Task B [T2]). Therefore, contrary to order repetition trials, there was a task repetition at the level of subtasks across task-pairs. This difference in T1 between order repetition trials and order switch trials was used to show that there are order switch costs in T1 even though T1 performance in order switch trials should occur more easily due to the task repetition between T2 of trial *n*-1 and T1 of trial *n* than T1 performance in order repetition trials, which are accompanied by a task switch relative to T2 of trial *n*-1. Nonetheless, this difference reduced the comparability of the two trial types. Hence, using the order switching logic, Luria and Meiran (2003, 2006) were not able to isolate the effects of switching at the global level of task-pairs from the effects of switching at the local level of subtasks.

----Table 1----

To disentangle these effects, we devised a novel empirical approach, namely the task-pair switching logic, in which the order of subtasks across task-pairs is constant and only the sequence of task-pairs is varied. According to this logic, at least three tasks (e.g., A, B, & C) are combined to different task-pairs (i.e., PRP trials), whereby T2 is the same across all task-pairs (e.g., Task-pair 1 with A as T1 and C as T2; Task-pair 2 with B as T1 and C as T2). The sequence of the task-pairs is manipulated and performance is studied in *n*-1 task-pair repetition trials and *n*-1 task-pair switch trials.

The performance comparison across these trial types enables us to isolate an important effect occurring at the global level of dual-task processing. This effect is the "*n*-1 task-pair switch cost". These costs are computed in T1 and T2 as the performance difference in *n*-1 task-pair switch trials and *n*-1 task-pair repetition trials. The existence of these costs would indicate that information about task-pairs is activated in the course of dual-task processing and, hence, that T1 and T2 are represented as a higher-order task.

Importantly, since T2 of trial *n*-1 differs from T1 in trial *n* in both *n*-1 task-pair switch trials (e.g., Task-pair 1 with A as T1 and C as T2 in trial *n*-1 & Task-pair 2 with B as T1 and C as T2 in trial *n*) and *n*-1 task-pair repetition trials (e.g., Task-pair 2 with B as T1 and C as T2 in trial *n*-1 and Task-pair 2 with B as T1 and C as T2 in trial *n*), there is a task switch at the level of subtasks in both trial types. Hence, the task-pair switching logic ensures that task-pair

switching at the global level of dual-task processing is not confounded with task switching vs. task repetition at the local level of subtasks (see Table 1).

Koch and Rumiati (2006, Experiment 3) already found small *n*-1 task-pair switch costs of 20 ms. However, they used a visual T1 requiring a deferred non-speeded vocal response and a speeded auditory-manual T2 and did not focus on the costs of switching task-sequences, so that this effect was an additional finding which was not further elaborated in the discussion of their overall pattern of dual-task findings. In the present study, we focused on this effect by employing the traditional PRP paradigm with two speeded responses to achieve better comparability with the studies by Luria and Meiran (2003, 2006).

In addition to the examination of *n*-1 task-pair switch costs, the use of our novel task-pair switching logic in the context of three task-pairs allows the investigation of the hypothesis that persisting inhibition is a control mechanism at the global level of dual-task processing (Luria & Meiran, 2003). The question of whether inhibitory processes adjust the activation of task-pairs can be explored by comparing performance in *n*-2 task-pair repetition trials with that in *n*-2 task-pair switch trials. When performance in *n*-2 task-pair repetition trials (e.g., Task-Pair 3 → Task-Pair 2 → Task-Pair 3) is worse than in *n*-2 task-pair switch trials (e.g., Task-Pair 1 → Task-Pair 2 → Task-Pair 3), this would indicate that in trial *n*-1 (e.g., Task-Pair 2), the task-pair performed in trial *n*-2 was inhibited (e.g., Task-Pair 3) and that the aftermath of the inhibition elicited to the task-pair in trial *n*-2 has to be overcome, when returning to this task-pair in trial *n* (e.g., Task-Pair 3). Since, in *n*-2 task-pair switch trials, subjects perform a task-pair that was not inhibited, performance is better in *n*-2 task-pair switch trials than in *n*-2 task-pair repetition trials (see Figure 1). This experimental logic is known in the general task-switching domain as *n*-2 repetition paradigm (Mayr & Keele, 2000) and the described performance deteriorations in *n*-2 task-pair repetitions, compared to *n*-2 task-pair switches, are referred to as *n*-2 task-pair repetition costs (see Koch et al. 2010, for a review). However, this *n*-2 repetition logic has not been applied so far at the level of task-pairs in the context of an overlapping task paradigm.

----Figure 1----

In the present study, we report three experiments in which we addressed the global level of dual-task processing. In Experiment 1, we assessed *n*-1 task-pair switch costs and *n*-2 task-pair repetition costs using univalent stimuli and conceptually overlapping responses. In Experiment 2, we replicated Experiment 1 with physically overlapping response sets. Finally, in Experiment 3, we measured *n*-2 task-pair repetition costs using a task-pair sequence without immediate task-pair repetitions.

Experiment 1

The goal of Experiment 1 was to examine the global level of dual-task processing under improved methodological conditions. Using the task-pair switching logic as a novel experimental approach, we were able to isolate the effects of switching at the global level of dual-task processing from the effects of switching at the local level of subtasks. We implemented the task-pair switching logic into the PRP paradigm by generating three task pairs (i.e., higher-order tasks) and manipulating the sequence of these task-pairs. The manipulation of the task-pair sequence enabled us to explore whether switching task-pairs is associated with performance costs (*n*-1 task-pair switch costs). This would indicate that information about task-pairs is activated in the course of dual-task processing and, hence, that T1 and T2 are represented as a higher-order task. Moreover, the variation of the task-pair sequence allowed us to investigate whether the activation of task-pairs and, thus, of higher-order tasks is adjusted by inhibitory control processes (*n*-2 task-pair repetition costs).

In addition to the PRP effect, we hypothesized to find *n*-1 task-pair switch costs in T1 and T2, indicating that information about task-pairs is activated in the PRP paradigm. Moreover, we hypothesized, in line with the considerations of Luria and Meiran (2003), to find *n*-2 task-pair repetition costs. These costs would indicate that inhibition plays a crucial role with regard to *n*-1 task-pair switch costs.

Method

Participants. Twenty-four adults (18 women; 20 right-handed; *M* = 21.8 years; *SD* = 3.8) participated in exchange for partial fulfillment of course requirements. All subjects had normal or corrected-to-normal vision and intact auditory skills.

Stimuli, tasks, and responses. The visual stimuli consisted of three task cues, including the German words for side, orientation, and object (*Seite*, *Orientierung*, and *Objekt*), a fixation cross and eight pictures (S1; see Figure 2), showing either a black can or a black cup. The handles could be located to the left or right of the objects, while the objects were presented upright or upside down. All visual stimuli were centrally presented on a white background of a 17-inch screen positioned approximately 50 cm in front of the subjects. The fixation cross and the cues were presented in black 28-point Arial font. The pictures were 7 cm in height and 6 cm in width. Auditory stimuli were two tones (200 Hz and 600 Hz; S2).

----Figure 2----

Depending on the cue, T1 was to decide whether the handle was on the left or right side of the object (cue: side), to report whether the object was presented upright or upside down (cue: orientation), or to make a decision about whether the object was a can or a cup (cue:

object). Responses to S1 were made with the middle finger and the index finger of the left hand by pressing the *Y* or *X* key of a QWERTZ keyboard. In T2, the participants were asked to categorize the tones as low-pitch or high-pitch tones. Responses were entered with the index finger and the middle finger of the right hand using the *N* or *M* key.

The stimulus-response mapping for the orientation task and the object task was counterbalanced across subjects. In contrast, considering the spatial stimulus-response compatibility effect (e.g., Fitts & Deininger, 1954; Fitts & Seeger, 1953) and the spatial-musical association of response codes effect (e.g., Keller & Koch, 2006, 2008; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006), the response keys for the judgement about the handle location and that about the tone pitch were not counterbalanced across subjects. All participants responded to objects with a handle on the left side with the *Y* key and to those with a handle to the right side with the *X* key. In the auditory task, low-pitch tones were categorized with the *N* key and high-pitch tones with the *M* key. A reminder of key assignment was placed at the bottom of the screen.

By combining each type of T1 with T2, we generated three task-pairs. The first task-pair comprised the side judgement and the tone task; the second pair, the orientation judgement and the tone task; and the third pair, the object judgement and the tone task. Hence, T2 was identical in all task-pairs.

Procedure. The experiment was run in a single session with one subject at a time. It started with a practice block of 18 trials, followed by 8 experimental blocks, each consisting of 64 trials. Instructions encouraged subjects to place equal emphasis on speed and accuracy.

At the beginning of each trial, a task cue was presented for 400 ms, followed by a fixation cross for 100 ms. After this cue-stimulus interval (CSI) of 500 ms, the visual S1 was displayed for 100 ms. Appearing after an SOA of either 50 ms or 800 ms, the auditory S2 was presented for 100 ms. An inter-trial interval of 1,000 ms separated trials within a block (see Figure 3). The task-pair sequence was displayed randomly with the stipulation that there was the same number of *n*-1 task-pair repetition and *n*-1 task-pair switch trials.

----Figure 3----

Design. To explore whether information about task-pairs is activated during dual-task processing, T1 and T2 performances were analyzed based on a repeated-measures 2 × 2 mixed design with the within-subject independent variables *n*-1 task-pair sequence (*n*-1 task-pair repetition vs. *n*-1 task-pair switch) and SOA (50 ms vs. 800 ms). In a second analysis, we investigated based on a further repeated-measures 2 × 2 mixed design with the within-subject independent variables *n*-2 task-pair sequence (*n*-2 task-pair repetition vs. *n*-2 task-pair switch)

and SOA whether the activation of task-pairs is adjusted by inhibitory control mechanisms. The dependent variables were RT and error rates.

Results

Analysis I: *n*-1 task-pair sequence. Practice trials, the first trial in each experimental block, and trials deviating more than 3 *SD* from each individual's mean per condition were excluded from the RT analysis (T1: 1.8%; T2: 1.7%). Moreover, trials on which any response was incorrect and trials following an error were not included in the RT analysis. Separate analyses of variance (ANOVAs) were run on mean RTs (see Figure 4) and error rates (see Table 2).

----Figure 4 and Table 2----

T1. For RT1, there was a main effect of *n*-1 task-pair sequence, $F(1, 23) = 29.05$, $p < .001$, $\eta_p^2 = .56$, with slower responses in *n*-1 task-pair switch trials than in *n*-1 task-pair repetition trials (947 ms vs. 834 ms). Hence, we revealed *n*-1 task-pair switch costs of 112 ms. No other effects were significant, all *p*s > .84.

The ANOVA on error rates showed the main effects of *n*-1 task-pair sequence, $F(1, 23) = 4.42$, $p < .05$, $\eta_p^2 = .16$, and SOA, $F(1, 23) = 9.09$, $p < .01$, $\eta_p^2 = .28$, indicating more error-prone responses for *n*-1 task-pair switch trials than for *n*-1 task-pair repetition trials (11.4% vs. 10.6%; *n*-1 task-pair switch costs: 0.8 %) and for trials with a short SOA than for trials with a long SOA (15.1% vs. 6.9%; SOA effect: 8.2%). The SOA effect might suggest a speed-accuracy trade off for short SOA. However, in RT1, the SOA effect was not significant. The interaction of *n*-1 task-pair sequence and SOA was non-significant, $F < 1$.

T2. For RT2, the ANOVA yielded a main effect of task-pair sequence, $F(1, 23) = 26.50$, $p < .001$, $\eta_p^2 = .54$, reflecting slower responses for *n*-1 task-pair switch trials than for *n*-1 task-pair repetition trials (1136 ms vs. 1020 ms). Hence, we observed task-pair switch costs of 116 ms. Moreover, the main effect of SOA was reliable, $F(1, 23) = 542.98$, $p < .001$, $\eta_p^2 = .95$. RT2 was higher after a short SOA compared to a long SOA (1367 ms vs. 789 ms), resulting in a PRP effect of 578 ms.

For the accuracy data, the ANOVA showed a main effect of SOA, $F(1, 23) = 6.49$, $p < .05$, $\eta_p^2 = .22$, with more error-prone responses after a short SOA than a long SOA (6.7% vs. 5.5%), reflecting a PRP effect of 0.9%. All other effects were non-significant, all *p*s > .43.

Analysis II: *n*-2 task-pair sequence. In the second analysis, we excluded *n*-1 task-pair repetition trials and *n*-1 task-pair switch trials that did not include *n*-2 task-pair repetitions or *n*-2 task-pair switches. Only trials preceded by at least two correct trials were included.

Moreover, we discarded trials deviating more than 3 *SD* from each individual's mean per condition. The data of two subjects were rejected due to an overall error rate of > 30% in T1.[1]

T1. The ANOVA on mean RT1 for *n*-2 task-pair repetition trials and *n*-2 task-pair switch trials showed no significant effects (all *p*s > .27; see Figure 5). Contrary to our prediction, numerically, RT was higher in *n*-2 task-pair switch trials than in *n*-2 task-pair repetition trials (944 ms vs. 929 ms), but this trend was not significant in RT, $F < 1$.

Yet, for the error data, the main effect of *n*-2 task-pair sequence was significant, $F(1, 21) = 6.75$, $p < .05$, $\eta_p^2 = .24$. Opposite to our expectation, responses in *n*-2 task-pair switch trials were more erroneous than in *n*-2 task-pair repetition trials (15.5% vs. 10.4%; *n*-2 task-pair repetition benefit: 5.1%; see Table 2). Moreover, there was a trend toward more error-prone responses in trials with a short SOA than in trials with a long SOA (17.0% vs. 8.9%; SOA effect: 8.1%). However, the main effect of SOA fell just short of significance, $F(1, 21) = 4.21$, $p = .053$, $\eta_p^2 = .17$. The interaction of *n*-2 task-pair sequence and SOA was not significant either, $F(1, 21) = 2.65$, $p = .12$, $\eta_p^2 = .11$.

T2. For T2, there was a significant main effect of SOA in the RTs, $F(1, 21) = 392.26$, $p < .001$, $\eta_p^2 = .94$, indicating slower responses after a short SOA than a long SOA (1455 ms vs. 814 ms; PRP effect: 641 ms). The main effect of *n*-2 task-pair sequence was not significant, $F(1, 21) = 1.43$, $p = .25$, $\eta_p^2 = .06$. However, like in T1, RTs were numerically higher in *n*-2 task-pair switch trials than in *n*-2 task-pair repetition trials (1151 ms vs. 1118 ms). The interaction of *n*-2 task-pair sequence and SOA was non-significant, $F(1, 21) = 2.04$, $p = .17$, $\eta_p^2 = .09$.

The ANOVA for the error rates showed a trend toward more erroneous responses after a short SOA than a long SOA (7.4% vs. 5.5%). However, the main effect of SOA was not significant, $F(1, 21) = 3.66$, $p = .07$, $\eta_p^2 = .15$. The main effect of *n*-2 task-pair sequence (*n*-2 task-pair switch trials: 5.9% vs. *n*-2 task-pair repetition trials: 6.9%) and the interaction of *n*-2 task-pair sequence and SOA were non-significant either, $F(1, 21) = 2.15$, $p = .16$, $\eta_p^2 = .09$, and $F < 1$.

----Figure 5----

Discussion

As expected, we found a PRP effect indicating that overlapping task processing results in performance impairments. In addition to the PRP effect, we found *n*-1 task-pair switch costs in both tasks. Importantly, *n*-1 task-pair switch costs in T1 and T2 were of a comparable size, possibly indicating that *n*-1 task-pair switch costs in T2 were propagated from T1 to T2 and did not represent 'true' task-pair switch costs in T2 per se but refer to T1 only. Moreover, since there

were no *n*-2 task-pair repetition costs but rather an *n*-2 task-pair repetition benefit (as a general numerical trend, and significant in T1 error rates), we found no evidence that inhibitory processes are the source of *n*-1 task-pair switch costs.

Experiment 2

In Experiment 1, we found *n*-1 task-pair switch costs, indicating that information about task-pairs is activated during dual-task processing. This suggests that T1 and T2 in dual-task situations are cognitively represented as a higher-order task, covering the task-sets of both tasks. To ensure that the activation of the visual task set in T1 cannot persist to the next trial despite the intervening auditory T2 and, hence, that *n*-1 task-pair switch costs are due to impaired task-pair switch performance rather than to repetition priming benefits in T1 from one trial to the next, we ran Experiment 2 in which we increased between-task interference by using physically overlapping responses.

For the general task-switching domain, Gade and Koch (2007) showed that response-set overlap increases the interference between tasks and, more importantly, that the between-task interference induced by overlapping response sets is resolved by increasing the activation difference between the irrelevant task and the relevant task based on inhibition of the previous irrelevant task. The inhibition, measured as *n*-2 task-pair repetition costs, was most pronounced in the case of physically overlapping response sets. For this reason, in Experiment 2, we used physical response-set overlap.

Method

Participants. A new group of 24 subjects (20 women; 22 right-handed; M = 23.8 years, SD = 1.0) participated in exchange for partial fulfillment of course requirements. All subjects had normal or corrected-to-normal vision and no hearing impairments.

Stimuli, tasks, responses, procedure, and design. The stimuli, the tasks, the procedure, and the design were identical to those used in Experiment 1. However, in contrast to Experiment 1, subjects performed T1 and T2 using the index and middle finger of the dominant hand, resulting in physically overlapping response sets.

Results

Analysis I: *n*-1 task-pair sequence. We used the same outlier criteria as in Experiment 1. There were 2.0% outliers in T2 and 1.9% in T2.

T1. For RT1, the ANOVA revealed a main effect of *n*-1 task-pair sequence, $F(1, 23) = 43.40$, $p < .001$, $\eta_p^2 = .65$. Responses in *n*-1 task-pair switch trials were slower than in *n*-1 task-pair repetition trials (960 ms vs. 848 ms), reflecting *n*-1 task-pair switch costs of 112 ms. The main effect of SOA, $F(1, 23) = 2.97$, $p = .10$, $\eta_p^2 = .11$, and the interaction of SOA and *n*-1 task-

pair sequence, $F(1, 23) = 2.51$, $p = .13$, $\eta_p^2 = .09$, were non-significant. The ANOVA on error rates showed no significant effects, all *p*s > .16.

T2. For RT2, the ANOVA yielded the main effects of task-pair sequence, $F(1, 23) = 41.15$, $p < .001$, $\eta_p^2 = .64$, and SOA, $F(1, 23) = 842.51$, $p < .001$, $\eta_p^2 = .97$, indicating slower responses for *n*-1 task-pair switch trials than for *n*-1 task-pair repetition trials (1138 ms vs. 1011 ms; *n*-1 task-pair switch costs: 127 ms) and for trials with a short SOA than for trials with a long SOA (1371 ms vs. 778 ms; PRP effect: 593 ms). Moreover, the interaction of SOA and *n*-1 task-pair sequence was significant, $F(1, 23) = 6.42$, $p < .05$, $\eta_p^2 = .22$. The PRP effect was larger in *n*-1 task-pair switch trials than in *n*-1 task-pair repetition trials (631 ms vs. 553 ms). For the accuracy data, there were no significant effects, all $p > .28$.

Analysis II: *n*-2 task-pair sequence. For the second analyses, we used the same outlier criteria like in the *n*-2 task-pair sequence analysis of Experiment 1.

T1. The ANOVA on mean RT1 showed a significant main effect of SOA, $F(1, 23) = 4.94$, $p < .05$, $\eta_p^2 = .18$, reflecting faster responses with short than with long SOA (962 ms vs. 1007 ms). The relevant main effect of *n*-2 task-pair sequence was not significant (*n*-2 task-pair switch trials: 988 ms; *n*-2 task-pair repetition trials: 980 ms), $F < 1$, but there was a significant interaction of SOA and *n*-2 task-pair sequence, $F(1, 23) = 7.86$, $p < .05$, $\eta_p^2 = .25$, indicating *n*-2 task-pair switch costs of 56 ms with short SOA and *n*-2 task-pair repetition costs of 39 ms with long SOA. Post-hoc one-tailed *t*-tests showed that *n*-2 task-pair switch costs were significant, $t(23) = -1.78$, $p < .05$, $d = 0.17$, whereas *n*-2 task-pair repetition costs were non-significant, $t(23) = 1.55$, $p = .13$, $d = -0.10$.

For the accuracy data, there was a significant main effect of *n*-2 task-pair sequence, $F(1, 23) = 5.31$, $p < .05$, $\eta_p^2 = .19$, with more erroneous responses in *n*-2 task-pair switch trials than in *n*-2 task-pair repetition trials (6.3% vs. 5.0%), resulting in *n*-2 task-pair switch costs of 1.3%. All other effects were non-significant, all *p*s > .29.

T2. For T2, the ANOVA showed a significant main effect of SOA, $F(1, 23) = 456.31$, $p < .001$, $\eta_p^2 = .95$. Responses were slower with long than with short SOA (1478 ms vs. 851 ms; PRP effect: 627 ms). Like in RT1, the main effect of *n*-2 task-pair sequence was not significant, $F < 1$. However, there was a trend towards *n*-2 task-pair switch costs (44 ms) with short SOA and *n*-2 task-pair repetition costs (46 ms) with long SOA, $F(1, 23) = 4.00$, $p = .06$, $\eta_p^2 = .15$. Post-hoc one-tailed *t*-tests showed that neither *n*-2 task-pair switch costs nor *n*-2 task-pair repetition costs were significant, both *p*s > .14. For the accuracy data, there were no significant effects, all $F < 1$.

Discussion

In Experiment 2, we replicated *n*-1 task-pair switch costs in the context of physically overlapping responses, providing clearer evidence for the existence of higher-order representations in dual-task processing. Since the use of physically overlapping response sets should induce interference between T1 and T2, we assumed that it was necessary to reduce the activation of the visual task-set of T1 to perform the auditory T2, and hence, that the activation of the visual task-set in T1 could not persist to the next trial. Moreover, we again found *n*-2 task-pair switch costs instead of the expected *n*-2 task-pair repetition costs. Hence, like in Experiment 1, we found no evidence for inhibition as selection mechanism at the global level of dual-task processing.

Between-experiment comparison

To explore whether there was interference between T1 and T2 and whether the interference was increased with physical response-set overlap, we run a 2 × 2 × 2 × 2 ANOVA with the between-subjects variable experiment (Experiment 1 vs. Experiment 2) and the within-subjects variables *n*-1 task-pair sequence (*n*-1 task-pair switch vs. *n*-1 task-pair repetition), SOA (50 ms vs. 800 ms), and R-R compatibility (compatible vs. incompatible). The existence of R-R compatibility effects suggests between-task interference in dual-tasks (Logan & Gordon, 2001). To avoid redundancy, we report only effects including the experiment or the R-R compatibility variable.

Results

T1. The ANOVA for RT1 showed no significant effects including experiment and/or R-R compatibility, all *p*s > .16. For the accuracy data, there was a significant main effect of experiment, $F(1, 46) = 8.01$, $p < .01$, $\eta_p^2 = .15$, indicating higher error rates in Experiment 1 than in Experiment 2 (11.0% vs. 5.0%). This might be due to the number of physically different response alternatives across the experiments (4 vs. 2). The interaction of experiment and SOA was also significant, $F(1, 46) = 7.73$, $p < .01$, $\eta_p^2 = .14$. The SOA effect was larger in Experiment 1 than in Experiment 2 (8.2% vs. 0.6%). More importantly, there was also a significant main effect of (backward) R-R compatibility, $F(1, 46) = 11.62$, $p < .01$, $\eta_p^2 = .20$, with more error-prone responses in R-R incompatible trials than in R-R compatible trials (8.4% vs. 7.6%), suggesting that R2 response selection interfered with R1 response selection (Hommel, 1998). Post-hoc one-tailed *t*-tests showed that the backward R-R compatibility effect was significant for both experiments (Experiment 1: 1.0%; $t(23) = -2.37$, $p < .05$, $d = 0.10$; Experiment 2: 0.7%; $t(23) = -2.53$, $p < .001$, $d = 0.17$). All other effects were non-significant, all *p*s > .27.

T2. The ANOVA on RT2 showed no significant effects including experiment and/or R-R compatibility, all *p*s > .19. However, for the accuracy data, there was a significant interaction of R-R compatibility and experiment $F(1, 46) = 8.82$, $p < .01$, $\eta_p^2 = .16$, indicating a typical forward R-R compatibility effect of 1.2% in Experiment 1 (e.g., Koch & Prinz, 2002) and a reversed forward R-R compatibility effect of -1.0% in Experiment 2. Post-hoc one-tailed *t*-tests showed that the compatibility effects were significant in both experiments (Experiment 1: $t(23) = 1.77$, $p < .05$, $d = 0.25$; Experiment 2: $t(23) = -2.37$, $p < .05$, $d = -0.28$). The reversed forward R-R compatibility effect might suggest a tendency to avoid using the same finger for consecutive responses (see general discussion). There were no other significant effects, all *p*s > .34.

Discussion

The between-experiment comparison showed backward and forward R-R compatibility effects in both experiments. These compatibility effects indicate that T1 and T2 were not processed fully independently of each other and that there was between-task interference in both experiments (e.g., Heuer, 1991). However, in contrast to our assumption based on previous work using task switching (e.g., Koch & Gade, 2007), physical response-set overlap did not induce stronger between-task interference than conceptual response-set overlap, suggesting that conceptual response set overlap alone already results in considerable between-task interference as shown in the pattern of backward and forward R-R compatibility effects in Experiment 1.

Experiment 3

In contrast to our hypothesis that the activation of task-pairs is controlled by inhibition (see also Luria & Meiran, 2003), we found in Experiment 1 and 2 an *n*-2 task-pair repetition benefit instead of *n*-2 task-pair repetition costs. This benefit provides no evidence for inhibition as selection mechanism at the global level of dual-task processing and may rather indicate that persisting activation, which results in positive priming of the previous relevant task-pair representation, may be the primary source of *n*-1 task-pair switch costs. In Experiment 3, we aimed to re-examine the role of inhibition. As Philipp and Koch (2006) found for the task-switching domain that *n*-2 task repetition costs are reduced in the context of immediate task repetitions, we sought to examine if the same is true for *n*-2 task-pair repetition costs.

Since the between-experiment comparison suggested that there was between-task interference in Experiment 1 with conceptually overlapping response sets and the use of physical response-set overlap might be linked to the problem of general limitations with regard to the simultaneous motor response execution, we used conceptual response-set overlap to re-

examine the role of the selection mechanism at the global level of task-pair processing in Experiment 3. Hence, we replicated Experiment 1 without immediate task-pair repetitions.

Method

Participants. A new group comprising 24 subjects (20 women; 23 right-handed *M* = 23.5 years, *SD* = 3.6) participated in exchange for partial fulfilment of course requirements. All subjects had normal or corrected-to-normal vision and no hearing impairments.

Stimuli, tasks, responses and procedure. The stimuli, the tasks, the stimulus-response mappings, and the procedure were identical to those used in Experiment 1. However, Experiment 3 did not include immediate task-pair repetitions.

Design. T1 and T2 performances were investigated based on 2 × 2 repeated-measures designs with the independent within-subject variables *n*-2 task-pair sequence (*n*-2 task-pair repetition vs. *n*-2 task-pair switch) and SOA (50 ms vs. 800 ms).

Results

We used the same outlier criteria as in Experiment 1. The data of one subject were excluded from all analyses due to an overall error rate of > .30.[2]

T1. For T1, the ANOVA showed that the main effect of *n*-2 task-pair sequence was non-significant for both RTs, $F(1, 22) = 3.07$, $p = .09$, $\eta_p^2 = .12$, and error rates, $F(1, 22) = 3.35$, $p = .08$, $\eta_p^2 = .12$, indicating only a trend toward slower and more error prone responses in *n*-2 task-pair switch trials than in *n*-2 task-pair repetition trials (895 ms vs. 879 ms; 13.2% vs. 12.0%). That is, numerically, we found an *n*-2 task-pair repetition benefit of 16 ms and 1.2%. The main effect of SOA was significant, $F(1, 22) = 5.14$, $p < .05$, $\eta_p^2 = .19$. There were more erroneous responses in trials with a short SOA than in trials with a long SOA (16.5% vs. 8.7%; SOA effect: 7.8%). All other effects were not significant, all *F*s < 1.

T2. For RT2, the main effect of *n*-2 task-pair sequence was significant, $F(1, 22) = 5.62$, $p < .05$, $\eta_p^2 = .20$, indicating again slower responses in *n*-2 task-pair switch trials than in *n*-2 task-pair repetition trials (1017 ms vs. 998 ms; *n*-2 task-pair repetition benefit: 19 ms). Moreover, the main effect of SOA was significant, $F(1, 22) = 753.27$, $p < .001$, $\eta_p^2 = .97$. Responses were slower after a short SOA than a long SOA (1298 ms vs. 717 ms), resulting in a PRP effect of 581 ms. The interaction of *n*-2 task-pair sequence and SOA was non-significant, $F < 1$.

The ANOVA for the error rates showed no significant main effect of *n*-2 task-pair sequence (*n*-2 task-pair switch trials: 10.2% vs. *n*-2 task-pair repetition trials: 10.1%), $F < 1$. The main effect of SOA and the interaction of *n*-2 task-pair sequence and SOA were non-significant either, all *p*s > .16.

Discussion

In summary, we again observed an *n*-2 task-pair repetition benefit instead of *n*-2 task-pair repetition costs. Hence, we replicated the benefit in situations without immediate task-pair repetitions and again found no evidence for inhibition as a crucial selection mechanism at the global level of dual-task processing. Instead, the data suggest persisting activation (i.e., priming) of the previously abandoned task-pairs.

General discussion

The objective of the present study was to examine whether T1 and T2 in dual-task situations are represented as a higher-level task and whether inhibition adjusts the activation of these higher-level tasks. For this purpose, we used a newly developed experimental logic that enabled us to isolate the effects of switching at the global level of task-pairs from the effects of switching at the local level of subtasks. In already existing studies, switching between task-pairs was confounded with switching between subtasks (e.g. Luria & Meiran, 2003, 2006). By using four subtasks, we were able to fully disentangle these effects, so that the mechanisms of cognitive processing at the global level of dual tasks could be more precisely described than before. Moreover, by looking at *n*-2 task-pair repetition costs as an index of inhibitory control we were able to test more directly Luria and Meiran's (2003) suggestion that inhibition acts as a selection mechanism at the global level of dual-task processing.

In Experiment 1 with conceptual response-set overlap, we found a PRP effect and *n*-1 task-pair switch costs in T1 and T2. In Experiment 2, we replicated the *n*-1 task-pair switch costs with physically overlapping responses. Importantly, in both experiments, we observed an *n*-2 task-pair repetition benefit in the error rates of T1. This benefit was replicated in Experiment 3 in which no immediate task-pair repetitions were included.

Cognitive processing at the level of subtasks

In all experiments, we observed the expected PRP effect which indicated that the simultaneous processing of two tasks results in performance costs. Moreover, in Experiment 1 and 2, we found backward R-R compatibility effects, reflecting worse T1 performance with incompatible than with compatible R-R relations. Hence, during response selection for T1, there seems to be interference between T1 and T2 when different conceptual or physical responses are required (see also Schuch & Koch, 2004). The finding of backward R-R compatibility effects is not in line with a strict response selection bottleneck, which would require that T2 response selection has to wait until the completion of T1 response selection. Thus, according to this model, T1 processing cannot be influences by T2 processing. Therefore, the least what

these data imply is that T1 is not performed completely independently of T2 (e.g., Ellenbogen & Meiran, 2008; Hommel, 1998; Janczyk et al., 2014).

R-R compatibility effects were also found in T2, indicating that T2 performance was affected by T1 processing. In Experiment 1, T2 performance was worse when responses did not overlap at the conceptual level and, hence, were linked to competing concepts. In Experiment 2, T2 performance was hampered when responses did overlap at the physical level, reflecting worse performance with R-R compatibility than R-R incompatibility. The reason for this reversed forward R-R compatibility effect might be that R-R compatibility was linked to physical response repetitions, whereas R-R incompatibility was associated with physical response changes. In the case of response repetitions, a response was selected for T1 and then the same response was reselected with a different meaning in T2, resulting in interference between the current and the previous response meaning (Schuch & Koch, 2004).

Taken together, the pattern of forward and backward R-R compatibility effects indicate that there was interference between T1 and T2 in Experiment 1 with conceptual response set overlap and in Experiment 2 with physical response set overlap. Gade and Koch (2007) showed that between-task interference that is induced by response-set overlap is resolved by decreasing the activation of the competing task. Thus, it was necessary to decrease the activation of T1 during T2 processing. However, here we are mostly interested in more global dependencies at the task-pair level.

Cognitive processing at the level of task-pairs

In Experiment 1 and 2, we found T1 and T2 performances to be worse in *n*-1 task-pair switch trials than in *n*-1 task-pair repetition trials, resulting in *n*-1 task-pair switch costs. Hence, dual-task performance seems to be dependent on the task-pair presented in the previous trial, indicating that information about a task-pair was activated in the preceding trial. This suggests that T1 and T2 are cognitively represented as a task-pair or a higher-order task and that there are cognitive control mechanisms acting at a more global level of processing than that of the subtask itself, namely at the level of higher-order tasks.

An alternative explanation for the finding of *n*-1 task-pair switch costs might be that the activation of the visual task-set in T1 persisted to the next trial despite the intervening auditory T2. However, as indicated by the observed R-R compatibility effects, there was interference between T1 and T2 at the response level in the present study. Since it has been shown that between-task interference at the level of response sets is resolved by decreasing the activation of the previous task (e.g., Gade & Koch, 2007), it was arguably necessary to decrease the activation of the visual T1 response set during T2 processing. Hence, the data suggest that in

both experiments, task-pair switches hampered performance and that *n*-1 task-pair switch costs were not the result of the persisting activation of the visual T1 task-set.

Luria and Meiran (2003) proposed inhibition as a cognitive control mechanism acting at the global level of dual-task processing. Since we used three task-pairs in all experiments of the present study, we could test the inhibitory account based on the *n*-2 repetition costs paradigm (e.g., Koch et al., 2010). Grange, Juvina, and Houghton (2013), who developed a computational cognitive model about inhibition in task switching, showed that the absence of reliable *n*-2 task repetition costs does not necessarily imply the absence of inhibition. The lack of *n*-2 task-pair repetition costs in the present study could mean that inhibition occurred at the global level of dual-task processing, but the inhibition might decay so fast that there is no inhibitory aftermath left in the *n* + 2 task-pair repetition trial or that the inhibition reduced the task-pair activation back to the baseline, rather than going below. According to the computational model by Grange and colleagues (2013), only the existence of *n*-2 task repetition benefits can assure that no inhibition occurred. For example, if in a "Task-Pair 3 → Task-Pair 2 → Task-Pair 3" sequence no inhibition is applied to Task-Pair 3 in trial *n*-1, then the activation of Task-Pair 3 should persist and prime performance.

In all experiments of the present study, in contrast to the inhibition hypothesis, performance in *n*-2 task-pair switch trials was more impaired than that in *n*-2 task-pair repetition trials, resulting in an *n*-2 task-pair repetition benefit (significant and as a numerical trend). A direct comparison of Experiment 1 and Experiment 3, which differ only with regard to the existence of immediate task-pair repetitions trials, showed that the benefit was numerically more pronounced in Experiment 3, where no immediate task-pair repetitions were included (consistent with previous findings by Philipp & Koch, 2006, on *n*-2 task repetition costs).[3]

Based on the computational cognitive model by Grange and colleagues (2013), we concluded that the finding of an *n*-2 task-pair repetition benefit does not provide evidence for inhibition as a cognitive mechanism regulating the activation levels of task-pair representations. Rather, persisting activation, which results in residual positive priming of the previously relevant task-pair representation, seems to be the source of *n*-1 task-pair switch costs, even though inhibition could not be fully excluded as a potential mechanism involved in higher-order task-pair control.

Following the idea of residual positive priming, the experience with a task-pair (i.e., the processing of a task-pair) results in an increased activation of its stimuli, responses, or/and S-R mappings, which facilitates processing when the same task-pair has to be performed again (see Richardson-Klavehn & Bjork, 1988, for a review). According to this logic, in *n*-1 task-pair

repetition trials, the relevant task-pair is more activated than the irrelevant one because the former has already been performed in the preceding trial, leading to a facilitation of the relevant S-R mappings and, hence, to performance benefits.

While the *n*-1 task-pair switch cost in T1 reflects 'real' processing costs, resulting from impaired task-pair switch performance probably due to persisting activation, it is not clear whether the observed *n*-1 switch costs in T2 are due to task-pair switching or whether they are simply propagated from T1 into T2. Such a propagation effect can be explained using dual-task models of structural limitations of the cognitive architecture, such as the response-selection bottleneck model (e.g., Pashler, 1994). Specifically, in the case of an *n*-1 task-pair switch, response selection for T1 slows down because new stimulus-response mappings have to be retrieved and implemented. Following the response-selection bottleneck model, T2 response selection starts after the completion of T1 response selection, which is why the prolongation in T1 response selection propagates into T2 at least with short SOA, where it slows down RT2 for the same amount of time. This explanation of *n*-1 task-pair switch costs in T2 is supported by the finding of comparable *n*-1 task-pair switch costs in T1 and T2, and by the used experimental design in which T2 was the same across task-pairs and, hence, in *n*-1 task-pair switch trials and *n*-1 task-pair repetition trials

Additional evidence for the assumption that *n*-1 task-pair switch costs in T2 are a result of a propagation effect is provided by the interaction of *n*-1 task-pair sequence and SOA in T2. *N*-1 task-pair switch costs were smaller after a long SOA than a short SOA. This indicates that in the case of a long SOA, the slowed response selection in T1 in task-pair switch trials can be absorbed during the waiting period until the response selection bottleneck becomes available for T2, resulting in decreased *n*-1 task-pair switch costs. In the case of a short SOA, perceptual processing for both tasks begins and ends almost at the same time, so that response selection is required simultaneously for T1 and T2. Since response selection cannot take place in parallel, T2 has to wait until the response selection bottleneck becomes available, resulting in large *n*-1 task-pair switch costs. Hence, the reduced *n*-1 task-pair switch costs in T2 with long SOA might represent residual *n*-1 task-pair switch costs that propagated from T1 into T2.

At the same time, however, this interaction of *n*-1 task-pair sequence and SOA also provides additional information about the effect of global processing on the PRP effect. The PRP effect was larger in *n*-1 task-pair switch trials than in *n*-1 task-pair repetition trials. This finding is in line with that of Luria and Meiran (2003), who also found this interaction in the context of subtask order switching. This overadditive interaction indicates that the PRP effect

increases when more cognitive control is required at the global level of dual-task processing and highlights the importance of the global processing level for dual-task performance.

Conclusions

Using a novel experimental approach in the present study, we showed a new empirical phenomenon in terms of *n*-1 task-pair switch costs. Based on this finding, we concluded that T1 and T2 are grouped together to a single hierarchical higher-order task, representing a higher-level connection between the task set of T1 and that of T2. In other words, subjects form a mental representation covering both task sets. We found no evidence for inhibition as a crucial selection mechanism at the level of higher-order tasks. Altogether, our study highlights the role of the global level of dual-task processing for dual-task interference and shows that the global processing level needs to be considered in future research on dual tasks and in models about dual-task processing.

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Footnotes

[1] When all subjects were used for the data analysis, the marginally significant main effects of SOA in the error rates of T1 and T2 became significant. More specifically, there was a significant SOA effect of 9.8%, $F(1, 23) = 6.63$, $p = .017$, $\eta_p^2 = .22$, and a significant PRP effect of 2.4%, $F(1, 23) = 5.24$, $p = .032$, $\eta_p^2 = .18$.

[2] The excluded participant used the x- and c-key instead of the y- and x-key from the fifth block to the eighth block.

[3] The *n*-2 task-pair repetition benefit was numerically larger in Experiment 3 without immediate task-pair repetitions than in Experiment 1 with immediate task-pair repetitions. However, an ANOVA with the additional between-subjects variable experiment (Experiment 1 vs. Experiment 2) showed that the size of the *n*-2 task-pair repetition benefit did not differ depending on whether there were *n*-1 task pair repetition trials included in the task-pair sequence, all *p*s > .12.

Table 1

Transitions at the global task-pair level and the local subtask level in the present paradigm and the paradigm by Luria and Meiran (2003, 2006).

Task-pair sequence	Global task-pair repetition	Local T2-T1 switch
Luria & Meiran (2003, 2006)		
AB → AB	✓	✓
BA → BA	✓	✓
AB → BA	×	×
BA → AB	×	×
Present paradigm		
AC → AC	✓	✓
BC → BC	✓	✓
BC → AC	×	✓
AC → BC	×	✓

Table 2

Mean error rates (in percentage; standard errors in parenthesis) in Experiment 1, Experiment 2, and Experiment 3 for Task 1 (T1) and Task 2 (T2) as a function of stimulus onset asynchrony (SOA; 50 ms vs. 800 ms) and task-pair sequence (n-1 task-pair repetition vs. n-1 task-pair switch & n-2 task-pair repetition vs. n-2 task-pair switch).

	T1		T2	
	SOA 50 ms	SOA 800 ms	SOA 50 ms	SOA 800 ms
Experiment 1				
n-1 task-pair switch	15.5 (3.2)	7.4 (1.3)	6.3 (1.3)	4.6 (0.8)
n-1 task-pair repetition	14.7 (2.9)	6.4 (1.5)	7.1 (1.1)	6.4 (1.0)
n-1 task-pair switch costs	0.8	1.0	-0.8	-1.8
n-2 task-pair switch	20.8 (4.9)	10.3 (1.6)	7.9 (1.8)	5.9 (1.2)
n-2 task-pair repetition	13.3 (3.8)	7.5 (1.4)	6.8 (1.9)	5.0 (1.3)
n-2 task-pair repetition costs	7.5	2.8	1.1	0.9
Experiment 2				
n-1 task-pair switch	5.8 (1.0)	5.0 (0.9)	5.2 (0.8)	4.7 (0.7)
n-1 task-pair repetition	4.9 (0.9)	4.6 (1.1)	4.9 (0.6)	4.5 (0.9)
n-1 task-pair switch costs	0.9	0.4	0.3	0.2
n-2 task-pair switch	6.9 (1.4)	5.6 (1.1)	4.8 (1.0)	4.9 (0.8)
n-2 task-pair repetition	4.7 (0.9)	5.2 (0.9)	4.1 (0.9)	4.6 (0.9)
n-2 task-pair repetition costs	2.2	0.4	0.7	0.3
Experiment 3				
n-2 task-pair switch	17.1 (3.7)	9.4 (1.4)	11.0 (1.7)	9.4 (1.6)
n-2 task-pair repetition	15.9 (4.8)	8.1 (1.6)	10.3 (1.9)	9.8 (1.5)
n-2 task-pair repetition costs	1.2	1.3	0.7	-0.4

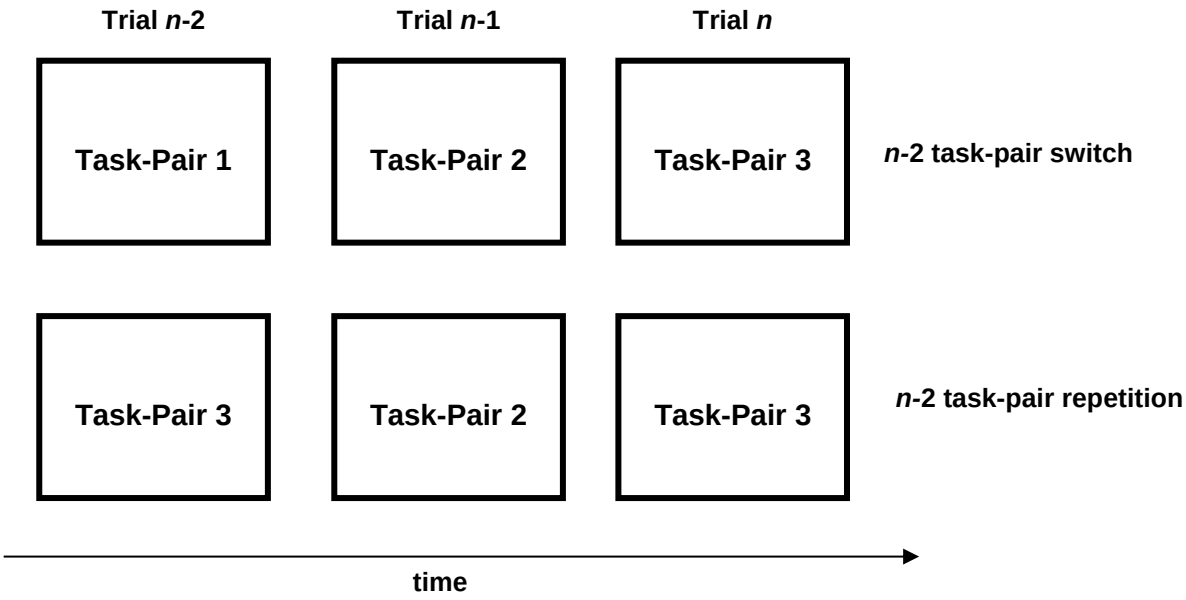

Figure 1. Sequence of events in *n*-2 task-pair switch trials and *n*-2 task-pair repetition trials.

Figure 2. Visual stimuli used in Experiment 1 and Experiment 2. Each object was presented either in the left or right orientation and either upright or upside down.

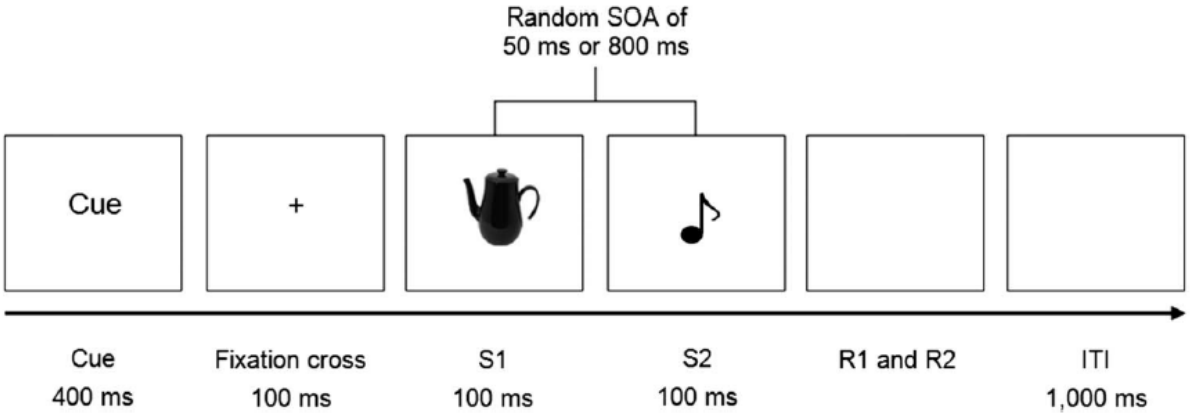

Figure 3. Timeline of events within an experimental trial. Each trial started with the presentation of a task cue for 400 ms, followed by a fixation cross for 100 ms. After this cue-stimulus interval (CSI), the visual S1 was displayed for 100 ms. Appearing after an SOA of either 50 ms or 800 ms, the auditory S2 was presented for 100 ms. The next cue was displayed 1,000 ms (inter-trial interval, ITI) after the response to S2 (R2) was executed.

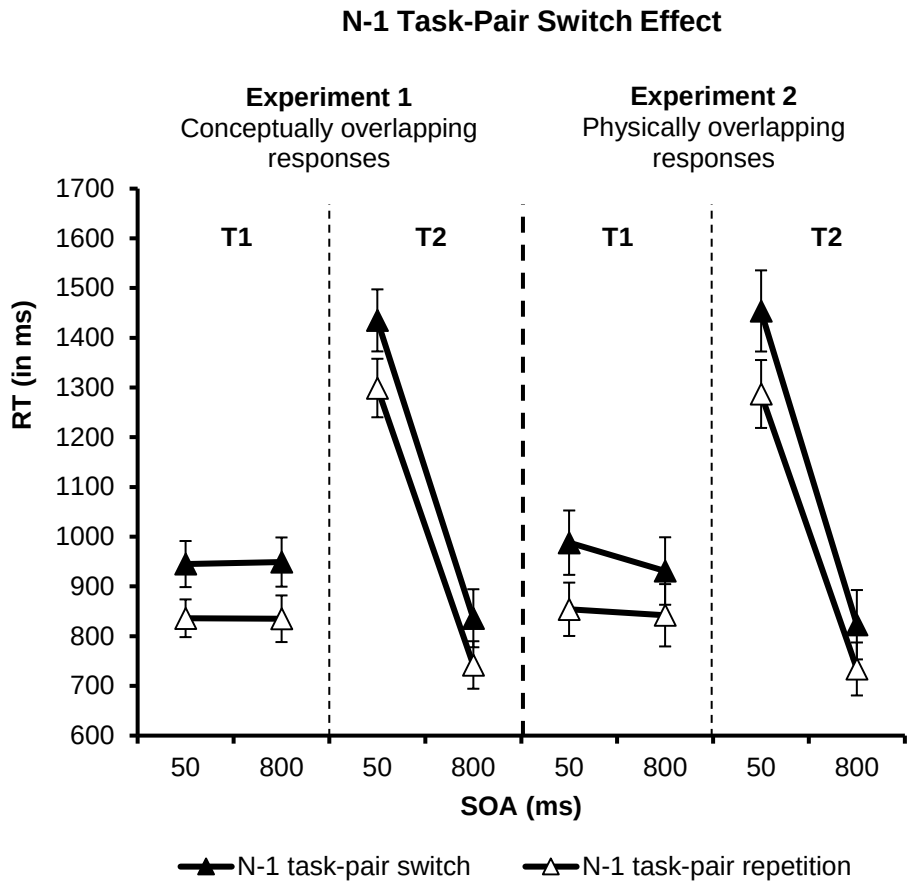

Figure 4. RT (in ms) in Experiment 1 and Experiment 2 for Task 1 (T1) and Task 2 (T2) as a function of *n*-1 task-pair sequence (*n*-1 task-pair switch vs. *n*-1 task-pair repetition) and SOA (50 ms vs. 800 ms).

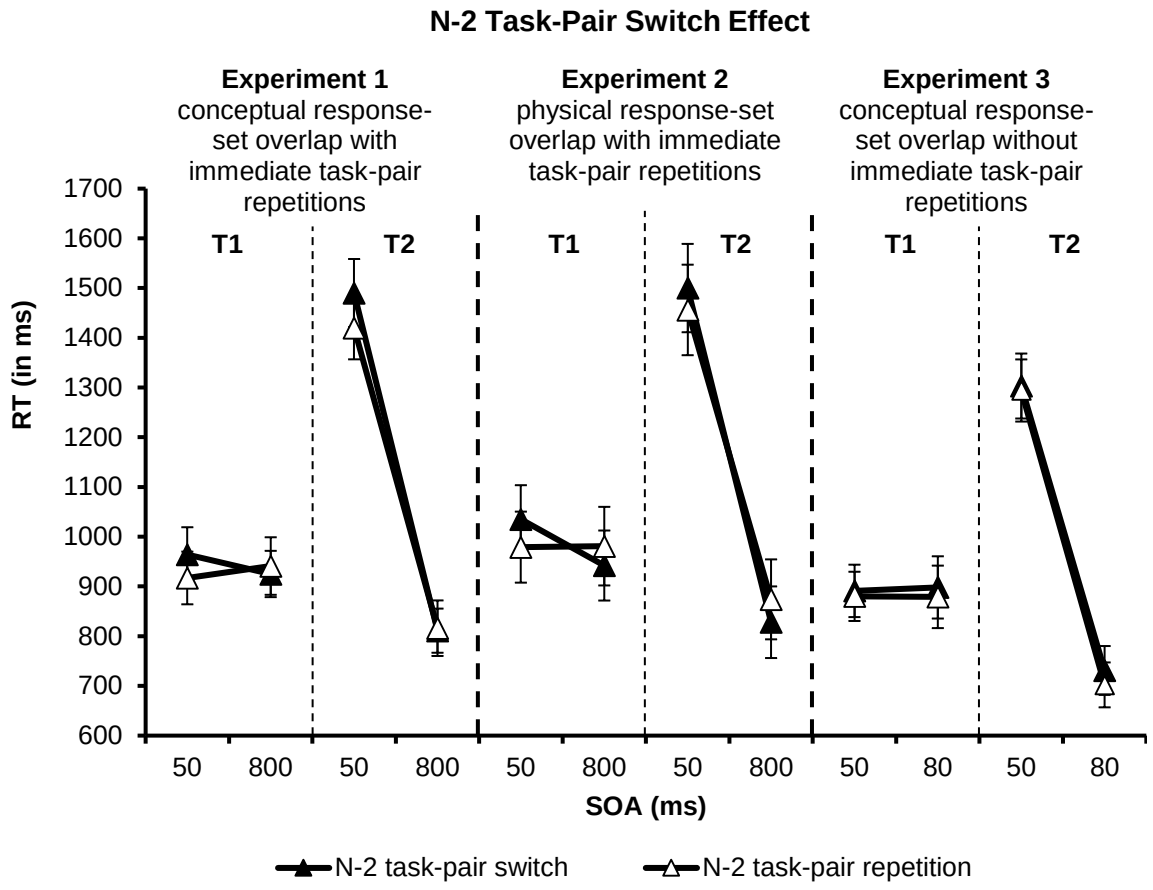

Figure 5. RT (in ms) for Task 1 (T1) and Task 2 (T2) as a function of *n*-2 task-pair sequence (*n*-2 task-pair switch vs. *n*-2 task-pair repetition) and SOA (50 ms vs. 800 ms) in Experiment 1 (conceptual response-set overlap with *n*-1 task-pair repetitions), Experiment 2 (physical response-set overlap with *n*-1 task-pair repetitions), and Experiment 3 (conceptual response-set overlap without *n*-1 task-pair repetitions).