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Cognitive Structure, Flexibility, and Plasticity in Human Multitasking – An Integrative Review of Dual-Task and Task-Switching Research

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Abstract

Numerous studies showed decreased performance in situations that require multiple tasks or actions relative to appropriate control conditions. Because humans often engage in such multitasking activities, it is important to understand how multitasking affects performance. In the present article, we argue that research on dual-task interference and sequential task switching has proceeded largely separately using different experimental paradigms and methodology. In our article we aim at organizing this complex set of research in terms of three complementary research perspectives on human multitasking. One perspective refers to structural accounts in terms of cognitive bottlenecks (i.e., critical processing stages). A second perspective refers to cognitive flexibility in terms of the underlying cognitive control processes. A third perspective emphasizes cognitive plasticity in terms of the influence of practice on human multitasking abilities. With our review article we aimed at highlighting the value of an integrative position that goes beyond isolated consideration of a single theoretical research perspective and that broadens the focus from single experimental paradigms (dual task and task switching) in order to favour instead a view that emphasizes the fundamental similarity of the underlying cognitive mechanisms across multitasking paradigms.

Key words: Attention, Multitasking, Dual Task, Task Switching, Cognitive Control

Public Significance Statement

This integrative review organizes the traditionally quite separate research areas of dual-task performance and task switching according to three different research perspectives. These perspectives differ in terms of their focus on cognitive structure, flexibility, and plasticity. With our review article we aimed at highlighting the value of an integrative position that goes beyond isolated consideration of a single theoretical research perspective and that broadens the focus from single experimental paradigms (dual task or task switching) in order to favour instead a view that emphasizes the fundamental similarity of the underlying cognitive mechanisms across multitasking paradigms.

COGNITIVE STRUCTURE, FLEXIBILITY, AND PLASTICITY IN HUMAN MULTITASKING – AN INTEGRATIVE REVIEW OF DUAL-TASK AND TASK-SWITCHING RESEARCH

Humans regularly engage in multitasking activities, even though this often causes performance costs in the individual tasks. Research on such limitations of multitasking can reveal fundamental aspects of cognitive architecture and the mechanisms of information processing. However, this theoretical issue has been examined by using a diversity of experimental paradigms that vary the degree of temporal and conceptual overlap in processing of two (or more) tasks. Given that these paradigms differ in terms of how tasks are combined, the term "multitasking" is not easy to define.

In fact, there is no strict definition of what constitutes a "task." The term "task" typically refers to a cognitive or behavioural goal that is either instructed or self-instructed, and the resulting representation of the corresponding cognitive and motor requirements has been termed "task set" (see, e.g., Kiesel, Steinhauser, Wendt, Falkenstein, Jost, Philipp, & Koch, 2010; Monsell, 1996, 2003; Sakai, 2008, for discussions of the concept of task set). Here we define the term broadly, so that simple stimulus-response (S-R) translations (e.g., press a response key when seeing the letter A), continuous tasks like visuo-motor tracking, complex mental operations (like multiplication), or complex movements (e.g., throwing a ball) can constitute a task if a person aims to achieve a discriminable goal state. Of course, such a broad definition can lead to inconsistencies, especially for hierarchical tasks or multi-step tasks. Depending on the systemic level of the description, one may consider a sub-goal or a single processing step as well as the higher-order goal or the complete sequence of steps as a "task" (see, e.g., Monsell, 1996, for a review).

Notwithstanding such potential terminological inconsistencies associated with the concept of a task, we speak of "multitasking" when cognitive processes involved in performing two (or more) tasks overlap in time (i.e., when two task sets need to be maintained at the same time). It is thus a defining characteristic of multitasking that time constraints exist, which prevent that each task is performed in temporal isolation. Moreover, it is sufficient that cognitive processes, like updating the task rules in working memory, keeping in mind the current status of a task, or evaluating the outcome of a task, occur concurrently in time across different tasks and are thus simultaneously mentally represented. Consequently, in addition to dual tasks that call for concurrent, simultaneous motor responses, serial task switching as well as task interruptions and resumptions fall within our definition of multitasking.

The Aim of the Review

In this review, we focus mainly on dual-task performance and task switching because these are the most frequently studied empirical phenomena. Yet, research on dual-task performance and task-switching performance refers to largely independent research traditions, so that empirical and theoretical developments proceeded more or less separately. The theoretical approaches, the specific research questions, and the empirical effects differ across the diverse paradigms even though these paradigms share the interest in multitasking as an overarching research topic. This diversity suggests the need for an integrative review. The aim of this review article is to integrate this complex set of research in these two related research areas by organizing it according to three different theoretical perspectives, focusing on the issue of cognitive structure, flexibility, and plasticity.

The *structural perspective* is primarily inspired by communication and information theory and later on by the computer metaphor of human cognition and strives to examine the basic elements of the architecture of the cognitive system. A core idea refers to the notion of abstractly defined information processing stages. In comparison, the *flexibility perspective* takes into account the enormous human ability to adapt behavior, within the bounds of the existing cognitive structure, in a moment-to-moment fashion to new situations and tasks. This includes flexible task-specific codes and categories as well as sensory-motor modality mappings, as represented in the currently active task set. Finally, the *plasticity perspective* aims to explore the learning processes that can change aspects of the internal organization of the cognitive processes underlying task-specific performance. Hence, while cognitive flexibility is the precondition for basic adaptation to changing situations and tasks, the structural and the plasticity perspective are complementary to each other (see Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010, for a review and discussion of cognitive plasticity). We argue that these perspectives are not competitive but should be seen as complementary, referring either to the current status of the cognitive system (structure, flexibility) or its dynamic change (plasticity).

In the present article, we argue that research in the family of dual-task paradigms has been predominantly guided by a different research perspective than research using the family of task-switching paradigms. Specifically, the majority of research on dual-task interference focused on more *structural* issues, such as locating the functional processing stage of the dual-task “bottleneck” (e.g., Broadbent, 1958; Pashler, 1994). In comparison, the majority of research in the area of task switching focused more strongly on issues of cognitive *flexibility*, referring to additional processes such as “reconfiguration” of processing mode and to higher-order representations in terms of “task set” (e.g., Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995). In particular, in research on task switching the role of active preparation (i.e., advance reconfiguration) has played a central role (see Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010, for reviews). In comparison, preparatory processes have received much less research attention in the area of dual-task research.

Importantly, research on the impact of practice on the costs of multitasking found that these costs decrease both for dual-task performance (e.g., Schumacher, Seymour, Glass, Fencsik, Lauber, Kieras, & Meyer, 2001; Van Selst, Ruthruff, & Johnston, 1999) and task switching (e.g., Karbach & Kray, 2009; Minear & Shah, 2008). Such practice effects[1] demonstrate considerable *plasticity* of cognitive-motor processes in multitasking (see, e.g., Strobach, Salminen, Karbach, & Schubert, 2014), which suggests a stronger integration of dual-task and task-switching research by grounding both in terms of common basic learning and memory mechanisms.

Yet, currently, research on multitasking is characterized by a spread across different experimental paradigms and theoretical perspectives. Major general reviews are no longer recent both in the area of dual-task interference (e.g., Lien & Proctor, 2002; Pashler, 1994; Schubert, 2008) and task switching (e.g., Kiesel et al., 2010; Monsell, 2003; Vandierendonck et al., 2010), or they focus on specialized subareas (e.g., dual-task interventions: Boisgontier , Beets, Duysens, Nieuwboer, Krampe, & Swinnen, 2013; practice effects in dual tasks: Strobach & Schubert, 2017a; inhibition in task switching: Koch, Gade, Schuch & Philipp, 2010; cue processing in task switching: Jost, De Baene, Koch & Brass, 2013; neuroimaging of task preparation in task switching: Ruge, Jamadar, Zimmermann & Karayanidis, 2013). Importantly, reviews that integrate more recent developments in both dual-task and task-switching research are lacking entirely. Specifically, the only review article we are aware of that explicitly attempted to relate dual-task performance and task switching is a book chapter published more than 15 years ago by Pashler (2000). At that time, he had to conclude that the "study of task set is in its relative infancy, and the suggestions offered here about how we might relate task set to dual-task limitations are modest and preliminary" (p. 302).

However, given that there has been considerable progress both in research on dual tasks and task switching, we argue that research on multitasking would benefit from having an

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[1] The terms "practice" and "training" are often used interchangeably. Practice refers to learning by repetition more generally, whereas training is sometimes used to denote more specific practice schedules that are intended to lead to a specific result, such as transfer to conditions other than the exact training conditions ("transfer of training"). We believe that practice represents the more general term, so that we use it throughout without making a distinction to training.

up-to-date review. The general challenge that such a review has to meet is that multitasking is a vast research field with a very diverse set of empirical findings, experimental paradigms, and theoretical accounts. There is also a more specific challenge for such a review, which is the necessary restriction of the scope of this review. We have taken two major decisions. First, we decided to restrict this review to multitasking studies that used combinations of tasks that have motor requirements (as opposed to pure memory tasks) and in which RT is a major dependent variable. This way we excluded a large set of literature on divided attention and working memory and instead focused on motor performance. Second, because covering the wealth of neuroscience studies would be beyond the scope of this review, we restricted our review mainly to experimental studies focusing on behavioral performance measures.

Experimental Paradigms for Studying Human Multitasking

Experimental research on human multitasking offers a wide variety of experimental paradigms. We make a broad distinction between paradigms in which tasks (i.e., task stimuli) are presented more or less concurrently (dual tasks) and paradigms in which tasks are presented strictly sequentially (task switching). This distinction is schematically illustrated in Figure 1. First, we briefly describe these paradigms to give an overview before we discuss the theoretical implications of the corresponding empirical findings.

-- Figure 1 --

Dual-Task Paradigms

There are two versions of the dual-task paradigm. One version considers dual-task performance relative to single-task performance to assess dual-task interference (e.g., Pashler, 1998, for a review). A second version examines dual-task interference depending on the temporal overlap of both tasks. This is the Psychological Refractory Period (PRP) paradigm (Welford, 1952; see Pashler, 1994, for a review).

The dual-task vs. single-task approach is to measure performance in two tasks either alone or in combination (e.g., Spelke, Hirst, & Neisser, 1976). Typically, performance for an individual task is worse when performed in combination with another task than when it is performed alone (see, e.g., Huestegge, Pieczykolan, & Koch, 2014). This performance difference (i.e., cost) can be interpreted as dual-task interference. Notably, in the dual-task paradigm, there is either a single stimulus or two stimuli at the same time, and the task load is manipulated in an all vs. none manner (i.e., dual-task blocks vs. single-task blocks; see upper left panel of Fig. 1). Note that some dual-task studies also include single-task trials in dual-task blocks (e.g., Lussier, Gagnon & Bherer, 2012; Schumacher et al., 2001). Because these single-task trials cannot be predicted, participants have to keep both tasks ready in working memory, whereas in pure single-task blocks only one task set needs to be actively maintained. Performance is usually better in pure single-task conditions, and this difference is attributed to preparation and maintenance of multiple task sets (sometimes called “task-set costs”). In comparison, the difference between dual-task and single-task trials in dual-task blocks, keeping task load constant across conditions, may represent a “purer” measure of dual-task costs.

In comparison, the PRP paradigm consists of two speeded tasks for which reaction time (RT) is the primary dependent measure (henceforth called RT tasks). Both tasks are performed in combination (i.e., in dual-task blocks) but with varying temporal overlap (see upper right panel of Fig. 1). An advantageous feature of this paradigm is that it keeps task load constant while being able to track the time course of dual-task interference. Specifically, the stimulus-onset asynchrony (SOA) for the stimuli of both tasks (S1 and S2) is varied, so that, in the extreme case, the two stimuli can be presented simultaneously (i.e., with an SOA of 0 ms) or with a relatively large temporal distance (e.g., an SOA of 1000 ms). The typical finding is that performance in the first task (Task 1, henceforth T1) is quite unaffected by variations of the SOA, whereas performance in Task 2 (T2) deteriorates with shorter SOAs. That is, the more temporal overlap of task processing (i.e., the shorter the SOA) the more dual-task interference can be observed in T2. This is the so-called PRP effect (see Pashler, 1994, for a review).[2]

Notably though, in those dual-task paradigms that vary the SOA, the SOA is often not long enough to allow completely sequential task performance. This is different in paradigms that examine sequential task switching.

Task Switching

Multitasking can also be examined using variants of the *task-switching* paradigm (see Koch & Brass, 2013). In task switching, two (or more) different tasks are performed sequentially. One way to assess performance costs is to compare single-task conditions (e.g., AAAA) with mixed-task conditions, in which the tasks alternate (e.g., ABAB; "alternation costs"; Jersild, 1927; Spector & Biederman, 1976; Pashler, 2000; see also Hirsch, Schwarzkopp, Declerck, Reese, & Koch, 2016; Lawo, Philipp, Schuch, & Koch, 2012). However, compared to single-task conditions, task alternation includes both the switching requirement and the requirement to prepare and maintain two task sets. To better isolate the switching component, switch costs are usually assessed in mixed-task conditions (see lower right panel of Fig. 1), in which tasks can be repeated, too (e.g., AABB), so that task switches and repetitions can be contrasted on a trial-by-trial basis within one and the same

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[2] Similar SOA effects have also been observed in PRP-like paradigms that can be termed "hybrid" variants because they combine an RT task with a non-speeded perceptual task. For example, it has been found that encoding briefly presented simple stimuli, such as letters, for a short-term memory task as T1 also leads to decreased performance in T2 when the SOA is very short (e.g., Jolicoeur & Dell'Acqua, 1998; Koch & Jolicoeur, 2007; Koch & Prinz, 2002; Koch & Rumiati, 2006). Likewise, combining an RT task as T1 with a perceptual short-term memory T2 has been found to result in decreased T2 memory performance when the SOA is short (Jolicoeur, 1999; see Jolicoeur, Tombu, Oriet, & Stevanovski, 2002, for a review). Hence, PRP-like dual-task interference can also be observed in such hybrid paradigms. Moreover, a special case of a dual-task paradigm is the so-called attentional blink (AB) paradigm (e.g., Raymond, Shapiro, & Arnell, 1992; see Dux & Marois, 2009, for a review). In the present article, we do not cover the hybrid paradigms or the AB paradigm and focus on those dual-task paradigms that require stronger involvement of motor control aspects.

experimental block, keeping task load constant. The task could either occur in a predictable sequence (e.g., Rogers & Monsell, 1995; see also Koch, 2003, 2005), or the upcoming task is indicated by explicit task cues in otherwise unpredictable task sequences (e.g., Meiran, 1996; see also Jost et al., 2013, for a review). The switch costs in task switching represent a measure of the "local" costs of changing the task set in the context of interference from other active, competing task sets.

In addition, the more "global" costs associated with task switching relative to performing only a single task have been called mixing costs (see Figure 1, lower left panel). Most studies used mixed blocks containing both switches and repetitions and compared performance in repetition trials to that in single-task blocks, so that both conditions are "locally" identical (see Kiesel et al., 2010, for review). Note that this logic follows the same logic as the calculation of "task-set costs" in dual task. The mixing costs in task switching represent a measure of the global costs of preparation and maintenance of multiple task sets.

There also exist versions in which participants are asked to select the task in each trial themselves ("voluntary task switching"; e.g., Arrington & Logan, 2004, 2005; Yeung, 2010). Regardless of the methodological details, the typical finding is that performance is worse in task switches than in repetitions, giving a measure of task-switch costs (see, e.g., Jost et al., 2013; Kiesel et al., 2010; Monsell, 2003; Vandierendonck et al., 2010, for reviews).[3]

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[3] A further paradigm that requires sequential multitasking is the *language-switching* paradigm. In this paradigm, the required response, such as vocal picture-naming (i.e., word production), is either in one or the other language. The required language is either indicated by an explicit language cue (e.g., Meuter & Allport, 1999) or it is based on a predictable language sequence (e.g., Declerck, Koch, & Philipp, 2015, for a review and discussion). Such bilingual switching has been found to result in robust performance costs relative to language repetitions (see Declerck & Philipp, 2015, for a review).

Moreover, we also note *task interruptions* as a special case of task switching. Here, performance of a primary task is interrupted, either by a significant temporal break, requiring a "restart," or by an intervening task, so that the primary task needs to be resumed. In such cases, it is regularly observed that resuming an interrupted tasks results in "restart costs" or "interruption costs" (e.g., Allport & Wylie, 2000; Altmann, 2002; Gopher, Armony, & Greenshpan, 2000; Poljac, De Haan, & Van Galen, 2006; Poljac, Koch, & Bekkering, 2009; see Kiesel et al., 2010, for a review).

Summary

We have introduced the family of dual-task and task-switching paradigms and the specific measures that can be used to assess the various kinds of performance costs that can occur in these paradigms. In the following, we discuss the theoretical implications of these performance costs for the two paradigmatic approaches (dual task vs. task switching) in the context of the three different research perspectives (i.e., structure, flexibility, and plasticity).

Structural Perspective on Multitasking

Dual-Task Approach, Limited Capacity, and Processing Bottlenecks

In the classic dual-task approach (i.e., dual-task vs. single-task comparison), dual-task costs have often been explained by referring to a division of attention, which has been conceptualized as a limited processing capacity (Kahneman, 1973). Notably, the very idea of divided attention presupposes that dividing attention is in fact possible. Yet, already Broadbent (1958) has advanced a competing theoretical approach based on the information-theoretical notion of a processing channel, suggesting that only one channel can be fully processed at a time. His “single-channel” account assumed that more refined stimulus processing, such as categorization, cannot take place in two channels simultaneously, effectively creating a processing bottleneck or attentional “filter” that requires rapid channel switching in dual-task performance (see Lachter, Forster, & Ruthruff, 2004, for a review).

Importantly, both competing accounts make strong assumptions about cognitive architecture, either assuming a structurally defined limit of generic processing capacity or a more specific inability of processing two stimuli simultaneously through the same information channel, which is a more specific account focusing on temporally “early” processing stages of perception. These two general ideas (i.e., limited capacity and processing bottlenecks) are still prevalent in theorizing about multitasking (e.g., Marois & Ivanoff, 2005), even though they have been considerably refined over the years. Notably, this focus on structural aspects of cognitive architecture is complementary to the exploration of the mechanisms that generate cognitive flexibility, as we discuss later in the section on "Flexibility."

In fact, graded sharing of limited capacity seems to correspond to the "intuitive" idea of divided attention (see Pashler, 1998, for a historically oriented review). Actually, early dual-task research often used continuous tasks, such as auditory-vocal shadowing (i.e., repeating back verbal messages) or visuo-motor tracking (i.e., trying to keep a manual response device on target). For example, Allport, Antonis, and Reynolds (1972) asked pianists to play a piece of music at sight while shadowing verbal messages. That is, the response requirements often had a strong motor aspect (e.g., tracking) and a more continuous character (shadowing temporally extended verbal messages). Hence, using such response requirements invites (or even necessitates) calculating dependent measures that aggregate performance over some periods of time. Using such continuous tasks, it has often been found that some combinations of tasks are much easier than other task combinations. In addition, it has been found that dual-task practice can serve to reduce the interference quite considerably even with rather complex tasks.

Yet, while continuous tasks and aggregated performance measures demonstrate dual-task interference more on a "macro-level," this kind of experimental set-up may not reveal the sources of dual-task interference at a "micro-level." Specifically, it has been argued that flexible scheduling of tasks and task components (i.e., subprocesses) can result in a significant reduction of dual-task costs (Meyer & Kieras, 1997), so that existing bottlenecks can be effectively masked. Hence, using such tasks actually favors accounts in terms of cognitive flexibility by implying "higher-order" processes of scheduling, but they render it difficult to examine potential structural processing bottlenecks. Higher-order processes at the task level have been mostly explored in more recent research on task switching. However, in the area of dual-task research in the 1980's, there has arguably been some kind of a "structural turn" in the research perspective, away from flexible capacity-sharing accounts, due to the rise of the so-called PRP paradigm (see Pashler, 1984, 1994).

PRP Paradigm and the Structural Central Bottleneck

While theoretical accounts in terms of flexible and graded sharing of processing capacity seem to be intuitively highly attractive, it has been argued that processing is in fact much less flexible and governed by a structural bottleneck (see Pashler, 1984), much like it has had already been assumed by Broadbent (1958) in his single-channel account. However, the empirical evidence for this account does not come from the classic dual-task approach but from the PRP paradigm. This paradigm has been introduced early in the literature (Telford, 1931; Welford, 1952), but only after it was combined with an extension of additive-factors logic (see, e.g., Sternberg, 1969) to identify the critical processing stage(s) underlying dual-task interference (Pashler, 1984), it has become so highly popular that it has overshadowed to some degree the capacity-sharing accounts, at least for some time.

Research examining the functional locus of the PRP effect is typically based on the assumption that cognitive processing is organized in a sequence of discrete, serial processing stages (e.g., Sanders, 1998; Sternberg, 1969, 2011). Specifically, in the PRP paradigm, the tasks typically use isolated, clearly defined stimuli, like visually displayed letters or auditory tones, so that the SOA could be manipulated very precisely at the level of the millisecond (ms). Moreover, the response requirements typically call for a single key press or the vocal production of a single word, so that RT could be measured very precisely for each task response in each single experimental trial rather than requiring aggregation over many trials or over an extended period of "time on task." Using this methodology, the influence of SOA manipulations (i.e., the PRP effect) is extremely robust despite the fact that each of the two cognitive tasks is extremely simple. Moreover, the two stimuli are often presented in different modalities (e.g., visual vs. auditory) to prevent perceptual masking in unimodal conditions, and also the two responses are often required in different motor modalities (e.g., manual vs. vocal) to prevent motor response interference. Hence, it has been argued that the remaining dual-task costs, after minimizing perceptual and motor sources of interference, are due to processing at a “central” stage.

Generally, it is assumed that the central processing stage refers neither to sensory processes (perceptual stage) nor to effector-specific processes (motor stage) while it remains somewhat less clear how the term “central” can be defined positively. Usually, it is assumed that the central stage implies decision and response selection processes (Pashler, 1994). However, PRP-like effects can also be observed in so-called hybrid paradigms that combine an RT task with a non-speeded perceptual or memory task (see Jolicoeur et al., 2002, for a review), which is consistent with a more generalized notion of central processing. The important point is that processing at this stage is assumed to be severely capacity-limited and thus may cause a “central” bottleneck (Pashler, 1994). In the following, we focus on the discussion of dual-task interference with two RT tasks.

Based on the theoretical processing-stage framework, a sophisticated experimental methodology has been developed (“locus-of-slack” logic, see Pashler, 1994). Many empirical studies revealed that manipulations of variables that affect early, perceptual processing stages in Task 1 (T1) and that thus postpone response selection in T1 also postpone RT2 to a similar degree. Likewise, manipulations that slow down response selection in T1 also increase RT2, suggesting that the effect of such manipulations is propagated to performance in the second task. In contrast, manipulations of post-selection stages in T1 have only little influence on RT2. Moreover, manipulations of perceptual processes in T2 can have smaller effects on RT2 with very short SOA as compared to long SOA, suggesting that perceptual processing in T2 can occur in parallel to response selection in T1 (“absorption” in the slack), whereas the effect of manipulations of response selection in T2 is usually completely independent of SOA. Together, this complex pattern of empirical findings suggests that response selection is a capacity-limited process that does not occur simultaneously in both tasks (see Figure 2; see, e.g., McCann & Johnston, 1992; Pashler, 1994, for detailed discussions).

-- Figure 2 --

Note that methodological refinement and creative use of the PRP paradigm has led research to abandon the notion of a perceptual bottleneck and has replaced it with a central response-selection bottleneck.[4] According to this idea, processing at perceptual and motor stages can occur in parallel (see Pashler, 1994), which represents a strong structural assumption. Parallel but independent processing is possible only if the component processes run in separate stages or "modules" (see Barret & Kurzban, 2006, for a review), and it requires the existence of independent capacity for each of the subprocesses, so that they do not limit each other. These strong assumptions about the serial nature of cognitive processing stages have become contentious given theoretical developments with respect to shared coding processes for perception and action control (e.g., Hommel, 2009; Hommel, Müsseler, Aschersleben, & Prinz, 2001) and grounded cognition approaches, which generally assume strong mutual interactions of sensory and motor processes (e.g., Barsalou, 2008), calling the amodal nature of so-called central processes in question. Nevertheless, it seems fair to say that the assumption of serial stages together with the associated locus-of-slack logic represents a heuristically highly useful simplification that has fueled dual-task research very substantially.

A strong interpretation of the idea that response selection is the critical capacity-limited bottleneck process in multitasking would be that response selection in the two tasks is

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[4] Note that the terms "central bottleneck" and "response-selection bottleneck" are often used interchangeably. In the context of the PRP effect, the discussion usually revolves around the issue of whether response selection can proceed in two tasks in parallel, which explains the somewhat narrower notion of a response-selection bottleneck, which would be a more specific version of the more generic concept of a "central bottleneck."

strictly serial because it *cannot* proceed in parallel and thus represents a structural all-or-none bottleneck (Pashler, 1994). This central response-selection bottleneck account is a prototypical representative of a structural perspective on multitasking. However, less strict interpretations assume context-sensitive scheduling mechanisms that serve to produce optimized performance, which often lead to serial response selection, but parallel response selection would be possible in principle (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997; Miller, Ulrich, & Rolke, 2009; see Fischer & Plessow, 2015, for a review).

Parallel vs. Serial Processing. Parallel processing is a logical possibility even if the two central processing stages require access to a common, limited capacity. Accordingly, it has been argued that central processes, such as those required for response selection, can run in parallel for two tasks, but that parallel processing comes at a cost because central capacity is limited. Such a view has been proposed by a variety of formal models of dual-task performance (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997; Miller et al., 2009; Navon & Miller, 2002; Tombu & Jolicoeur, 2003). Notably, such models make very similar predictions as the serial response selection account (see, e.g., Byrne & Anderson, 2001). One particular theoretical difficulty when evaluating the success of serial vs. parallel models is that they agree on the notion that only “central” processes are capacity-limited, and that both types of model essentially represent versions of capacity sharing that differ primarily in the mechanisms of “sharing” (i.e., all-or-none vs. graded).

Yet, the notion of a serial bottleneck raises the issue of how access to the bottleneck is regulated. The structure of Pashler’s (1994) central bottleneck model implies an inflexible “first-come first-served” mechanism for determining the order of subtasks.[5] That is, access to the bottleneck stage in the second task would have to wait passively (“queuing”). However,

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[5] This “customer metaphor” has also been used by Pashler (1994) for explaining the basic bottleneck idea: “Everyone is familiar with this principle in another context: If one enters a bank right behind another customer and there is only one teller on duty, the teller represents a bottleneck.” (p. 224)

this is not the only logical possibility. The alternatives require "executive" control processes for determining the processing order of tasks (i.e., order of access to the serial bottleneck) in a more flexible way, but such control processes are beyond the scope of the original model (see, e.g., Lien, Ruthruff, Cornett, Goodin, & Allen, 2008; Logan & Gordon, 2001; Schubert, 2008, for review and discussion). Likewise, parallel processing and capacity-sharing models require additional control processes that determine the degree of parallel central processing (see Fischer & Plessow, 2015, for a recent overview). Importantly though, the notion of a limited central capacity is a strong assumption about the structure of the cognitive system.

Modality-Specific Effects. Largely independent of the serial vs. parallel issue, the exact nature of the limited processing capacity has been debated since the early research on multitasking. For example, Allport et al. (1972) found that dual-task interference increased if the two tasks were similar, that is, shared common processes. This notion of task similarity as determinant of dual-task costs has been extended to refer to combinations of stimulus modalities, task-specific processing codes, and output modalities. Modalities can be defined with reference to the sensory or motor systems that are necessarily involved in processing, so that, say, visual and auditory stimuli refer to different perceptual modalities, whereas manual and vocal responses refer to different motor modalities, independent of the specific content of the processed information. The content of processing would be reflected by different codes that could, for example, refer to verbal or spatial information (see Wickens, 1984, 2002). In this way, a generic processing capacity view is complemented by a view of separate modality- and code-specific resources. Specifically, it has been shown that dual-task costs are smaller if visual-manual and auditory-vocal modality mappings are combined compared to the reverse mappings (i.e., visual-vocal and auditory-manual), suggesting that these mappings produce less between-task crosstalk because they are more "naturally" associated within tasks (e.g., Hazeltine, Ruthruff, & Remington, 2006; see also Göthe, Oberauer, & Kliegl, 2016;

Greenwald, 1970; Greenwald & Shulman, 1973; Halvorson, Ebner, & Hazeltine, 2013; Halvorson & Hazeltine, 2015; Hartley, Seaman, & Maquestiaux, 2015; Lien, Proctor, & Allen, 2002; Liepelt, Fischer, Frensch, & Schubert, 2011, for further discussion).

Hence, even though most researchers agree that there is a limited-capacity processing bottleneck (be it serial or parallel), such findings raise the issue of the degree to which this dual-task bottleneck is central in the sense of being “amodal” or modality-specific (see Tamber-Rosenau, Dux, Tombu, Asplund, & Marois, 2013, for a discussion of neuroscience evidence). Note that the idea of limited capacity in modality-specific processing modules, together with the idea that the combination of such modules in dual-task requirements determines the degree of interference, represents a strong assumption about the structure of cognitive architecture. According to this view, the degree of dual-task interference would be primarily determined by the combination and the mapping of modality and code-specific subprocesses (see Huestegge et al., 2014; Huestegge & Koch, 2010, 2013, for a discussion) and less by an amodal bottleneck stage.

Task Switching and the Task-Set Reconfiguration Bottleneck

Unlike dual-task research, research on task switching is generally focused more on cognitive flexibility, such as the possibility for advance preparation of a task switch, rather than on structural aspects of information processing. Yet, the basic structural implications postulated in dual-task research have also been applied to sequential task switching.

From a structural perspective on task switching, a time-consuming “reconfiguration” of task set has been postulated. That is, an activated task set is assumed to be the precondition for performing a task, so that performing a task switch requires a switch in the mental task set because it might be structurally impossible to have two task sets activated at the same time. The process of activating and implementing a new task set is often called task-set reconfiguration, which reflects a switch-specific bottleneck process, just like an inserted processing stage (e.g., Monsell, Yeung, & Azuma, 2000; Rubinstein, Meyer, & Evans, 2001), as depicted in Figure 3. According to such accounts, reconfiguration takes some time, which is at least partly reflected in the size of the RT switch costs.

-- Figure 3 --

This stage-based idea invites similar experimental approaches as the PRP paradigm (Pashler, 2000), looking for variables that are assumed to affect a specific processing stage. A major variable is the time for task preparation. Many studies found reduced switch costs with more preparation time (Kiesel et al., 2010; Vandierendonck et al., 2010, for general reviews). The existence of preparation effects has been taken as evidence for the idea that this reconfiguration can take place to some degree prior to performing the actual task, that is, before presentation of the new target stimulus (Rogers & Monsell, 1995), so that the time needed for reconfiguration does no longer fully add to the RT.

However, note that even though preparation effects speak to the flexibility issue, the very existence of costs of task switching has relevant structural implications. Moreover, almost all studies found so-called residual switch costs that remain even after the preparation time has been extended to multiples of the switch cost itself, suggesting that there are sources of persisting interference that are not (or even cannot) be overcome by advance preparation for a task switch (e.g., Monsell, 2003). The residual costs seem to imply that there are structural limits of task preparation (see Lindsen & De Jong, 2010, for a critical discussion). Therefore, two-stage models of reconfiguration have been proposed. A first stage ("advance reconfiguration"; Rogers & Monsell, 1995; "goal shifting"; Rubinstein et al., 2001; see also Mayr & Kliegl, 2000) can be completed prior to target onset and thus represents cognitive flexibility, whereas the second component ("stimulus-cued completion"; "rule activation") can occur only when being triggered by the actual task stimulus and thus represents a structural limitation for final task readiness.

Parallel vs. Serial Processing. While the simplest version of a reconfiguration bottleneck would claim that reconfiguration is all-or-none (just like the response-selection bottleneck in dual tasks), such a strong structural claim has only rarely been made in task switching research (see, e.g., De Jong, 2000). In contrast, it has been acknowledged early on that reconfiguration is more gradual, representing more a bias that favors task-specific processing related to one task rather than the other, competing task (e.g., Gilbert & Shallice, 2002). For example, in Gilbert and Shallice's (2002) model of task switching using Stroop-like color-word stimuli (i.e., switching between color naming and word reading), there are "task demand units" that code the currently relevant task in terms of a bias exerted on the outcome of processing in "output" units. The output units and the nodes within the output units and the task demand units are mutually inhibitory. Notably, the task demand units themselves receive a higher-level control input that determines the type of bias that they exert. This higher-level input might come either from external task instructions or from internal monitoring processes (see, e.g., conflict monitoring; Botvinick, Braver, Barch, Carter, & Cohen, 2001; see also Brown, Reynolds, & Braver, 2007, for a related, more recent model).

The important aspect of this type of model is that it abandons the idea of a strictly all-or-none central bottleneck, as it is assumed in the central bottleneck model of dual-task performance or in a strong version of the task-set reconfiguration model. Instead, the processes underlying (serial) multitasking represent gradual shifts in terms of a biased competition (Desimone & Duncan, 1995) rather than all-or-none shifts in terms of necessary completion of a serial reconfiguration stage. In this vein, Meiran (2000) has suggested that there are actually separate biasing processes that serve to reconfigure the stimulus set (i.e., attentional settings governing stimulus selection) and the response set (i.e., intentional coding of response “meanings”; Schuch & Koch, 2004), and the very concept of a bias suggests that it is gradual (see also Meiran, Kessler, & Adi-Japha, 2008).

Importantly, a processing bias can be stronger or weaker, which would result in less or more parallel processing. This is a highly relevant structural assumption because typical task-switching studies use “bivalent” stimuli that can serve as a target for both tasks (e.g., number stimuli for switching between parity and magnitude judgments; see, e.g., Koch, 2003; Sudevan & Taylor, 1987). Some degree of parallel processing is implied by the finding of congruence effects, which occur if the two aspects of a bivalent stimulus are mapped to the same (vs. different) response key. For example, if the categories “odd” and “smaller than five” were both mapped to the left key, the stimulus 3 would be congruent (i.e., requiring a left key press response in both tasks), but the stimulus 4 would be incongruent (i.e., requiring different responses, depending on the task). Performance is typically worse in incongruent trials than in congruent trials (e.g., Kiesel et al., 2010, for a review). Congruency effects can be explained by parallel processing of the two aspects of the stimulus, and this explanation implies that reconfiguration of the task set (or of “stimulus set”) is not all-or-none and that parallel processing is prevalent in task switching (see Schneider, 2015, for a discussion).[6]

Modality-Specific Effects. Unlike in dual-task research, the issue of a strict all-or-none serial task processing is usually not part of the theoretical discourse in research on task switching (see Kiesel et al., 2010). Yet, in task switching, too, there are discussions about the

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[6] Note that only few studies compared performance with bivalent and univalent stimuli directly, but these studies usually found smaller switch costs with univalent than with bivalent stimuli. For example, in their Experiment 1 Rogers and Monsell (1995) compared switching between parity judgments and consonant vs. vowel judgments using either bivalent letter-digit compounds (e.g., G7) or univalent stimuli (e.g., G#) and found that switch costs were much higher with bivalent stimuli (289 ms) but still substantial with univalent stimuli (161 ms). Likewise, using a spatial task-switching paradigm introduced by Meiran (1996), Koch, Ruge, Brass, Rubin, Meiran, and Prinz (2003) found higher switch costs with bivalent stimuli (48 ms) than with univalent stimuli (18 ms). This influence of stimulus valence on switch costs may be due to the additional interference based on parallel response and task activation. However, switch costs are typically found with univalent stimuli, too, and can often be observed even in situations in which both the stimuli and the responses were non-overlapping (i.e., univalent; e.g., Stephan & Koch, 2011). Therefore, switch costs are not reducible to the effect of stimulus-based competition of S-R mappings.

modality-specificity of task interference. For example, Stephan and Koch (2010) found that switch costs were smaller when participants switched between auditory-vocal and visual-manual tasks than when they switched between auditory-manual and visual-vocal tasks (the same pattern arises when visual stimuli were replaced with tactile stimuli; Stephan & Koch, 2015). Note that the stimuli and responses were identical in both conditions, but only the modality mappings differed. Such findings are generally consistent with models claiming modality-specific processing resources, such as those proposed in research on dual tasks (e.g., Hazeltine et al., 2006; Wickens, 1984). However, Stephan and Koch (2011) argued more specifically that the benefit is due to multitasking crosstalk that arises from anticipating the response feedback. For example, vocal responses produce auditory feedback, so that anticipating auditory feedback in a modality-incompatible visual-vocal mapping would prime processing auditory input that actually refers to the competing auditory-manual task. This idea is consistent with "ideomotor" accounts of action control, stating that actions are controlled by representations of anticipated action effects (see, e.g., Badets, Koch, & Philipp, 2016; Greenwald, 1970; Kunde, Elsner, & Kiesel, 2007; Shin, Proctor, & Capaldi, 2010, for reviews). Hence, such ideomotor learning can increase between-task crosstalk as a function of response-based interference of task sets. For the present discussion it is important that the issue of modality-specificity of task processing in task switching is not expected (and not easily explained) by models that attribute switch costs to an amodal "central" reconfiguration bottleneck.

Integrative Summary

Both dual-task and task-switching research share a common interest in explaining human multitasking. Moreover, comparable findings are obtained in both research lines. For example, there are costs of multitasking in both paradigms, measured either as switch costs or dual-task costs (or the PRP effect). Also, there are more global multitasking costs even in trials that do not require a dual task or a task switch, such as those measured as task-set costs in dual-task performance (i.e., single-task trial in the dual-task blocks vs. single-task blocks) or as mixing costs in task switching (single-task blocks vs. repetition trials in mixed-task blocks). Furthermore, both paradigms show between-task congruence effects when using overlapping S-R mappings, such as with bivalent stimuli or responses.

Yet, despite the fact that issues of cognitive flexibility, such as graded sharing of processing capacity across tasks, have been raised in research on dual-task performance, the emphasis has been towards a more structural view in terms of a bottleneck at central processing stages (Pashler, 1994). In comparison, task-switching research focused more strongly on cognitive flexibility, such as when examining active task preparation, even though research in this paradigm also included significant assumptions about cognitive structure (e.g., reconfiguration of task set as an added processing stage).

When comparing research on dual-task and task-switching performance, it is noteworthy that both research lines predominantly focus on “central,” amodal sources of interference (e.g., Monsell, 2003; Pashler, 1994, 2000; Vandierendonck et al., 2010). Nevertheless, the issue of the degree to which task interference is determined by the compatibility of modality mappings across tasks has gained relevance in both dual-task research (e.g., Göthe et al., 2016; Hazeltine et al., 2006) and task-switching research (Stephan & Koch, 2010, 2015). Note that such an approach cannot be easily derived from a structural stage logic, thus calling for accounts that assume flexible, task-specific sensory-motor remapping processes that can produce modality-specific interference.

Interestingly, there are also notable differences in the structural research perspectives in dual-task and task-switching research. Specifically, in dual-task research, the focus is more on the issue of structural all-or-none bottlenecks and the associated issue of serial vs. parallel processing, but the issue of the mechanisms underlying the possible flexibility of processing, such as task scheduling or order control, have not received much research attention. In contrast, the issue of the “intentionality” of a shift in task set has always been of major interest in task-switching research (e.g., Allport et al., 1994; Rogers & Monsell, 1995), so that mechanisms allowing for cognitive flexibility, such as preparation, were in the research focus.

Flexibility Perspective on Multitasking

The issues of structural limitations and cognitive flexibility are complementary. The notion of a fixed, structural central bottleneck implies little flexibility at this specific processing stage (Pashler, 1994). Likewise, the idea of a task-set reconfiguration bottleneck when switching tasks also argues in favor of a structural limitation (Monsell, 2003). Yet, research on dual-task performance has assumed a flexible sharing of either general or modality-specific processing capacity (Navon & Miller, 2002; Wickens, 1984) and that the degree of sharing depends on exogenous factors such as task characteristics and endogenous factors such as arousal and effort (Kahneman, 1973). Likewise, a substantial share of research using the task-switching paradigm is actually devoted to preparatory processes that endow the system with cognitive flexibility. In this section, we first discuss the flexibility perspective in dual-task research and then turn to task-switching research, pointing out the commonalities in the research programs and empirical findings in these different research lines.

Flexibility in Dual-Task Processing

Early capacity sharing accounts of dual-task performance lack specificity with respect to the underlying processes, whereas the PRP paradigm has provided research with a powerful experimental tool to identify the processing stage of the assumed bottleneck. However, also in the PRP framework there has been a debate as to whether the access priorities and the processing rate of the bottleneck are subject to “strategic” processes that imply some flexibility. Dual-task models describe several different mechanisms related to cognitive flexibility. One refers to mechanisms of central capacity sharing, a second refers to between-task crosstalk, and a third to additional higher-level mechanisms of task-order control.

Central Capacity Sharing. One way to transfer the idea of capacity sharing to the PRP framework is to argue that there is a structural capacity limitation primarily at the central processing stage, but that the allocation of this capacity to the central processes of each task can occur in a gradual, flexible way. That is, while it is agreed that perceptual and motor-related processes can proceed in parallel to a smaller or larger extent (i.e., are less capacity-limited in the first place), parallel processing has also been claimed for the central stage. Importantly, such a central capacity sharing account still assumes competition for limited capacity, but the resolution of competition is more flexible. For example, Navon and Miller (2002) and Tombu and Jolicoeur (2003) argued that central capacity sharing models basically arrive at the same predictions as the structural all-or-none bottleneck model. Thus, the all-or-none model can be simply seen as a special variant of capacity sharing, in which case it becomes obvious that capacity sharing models represent the broader class of models.

Recent research has made some progress in identifying factors and underlying processes that govern the degree of capacity sharing. For example, Miller et al. (2009) showed that the distribution of SOAs influences the relative efficiency of serial and parallel processing modes. The data suggest that there is a shift from a more serial mode to a more parallel mode when short SOAs are more frequent than long SOAs. To account for such findings, Miller et al. (2009) proposed that performance is adaptive to the task constraints, so that a parallel mode can be more efficient than a serial mode (e.g., Lehle & Hübner, 2009; see Fischer & Plessow, 2015, for a review). Generally, such findings suggest that the ubiquitous evidence of serial processing in the PRP task results from performance optimization rather than from a structural bottleneck (see also Logan & Gordon, 2001, for discussion).

Yet, capacity-sharing models are still rooted in the structural logic referring to fixed, serial processing stages, even though they allow for more cognitive flexibility. The stage logic is a very abstract way of theorizing, and the reference to a central stage represents a placeholder for the actual codes and categories that need to be processed, mapped, and remapped in multitasking. In comparison, focussing on between-task crosstalk reflects a very different theoretical approach that takes the content (e.g., spatial “meaning”) and the nature (i.e., modality) of these codes into account.

Between-Task Crosstalk and Degrees of Parallel Processing. Crosstalk can be defined as the unwanted transmission of information (i.e., content, such as stimulus or response codes) from one information processing stream (“information channel”) to the other stream. Crosstalk can be a potent source of interference (e.g., Huestegge & Koch, 2010; Koch, 2009; Navon & Miller, 1987). Yet, typical illustrations of the central bottleneck model (see Figure 2) depict the performance of the two tasks as completely separate processing streams, suggesting by itself no way as to why, or how, between-task crosstalk at the level of content could arise. However, given the assumption that parallel processing occurs across stages except for response selection, it is possible to assume that the task processing channels are not fully shielded during parallel processing. If so, the central bottleneck model allows the derivation of very specific hypotheses for the type of crosstalk that should theoretically be possible (see Lien & Proctor, 2002, for a review).

Specifically, crosstalk effects from response selection in T1 on response selection in T2 are not part of the original response-selection bottleneck model, but such “forward” crosstalk could be accounted for by assuming that residual activation of T1 response codes can “spill over” to give some R2 priming for the subsequent response-selection processes to the degree that the set of T1 responses and the set of T2 response share some features (e.g., have dimensional overlap; see Kornblum, Hasbroucq, & Osman, 1990), that is, to the degree to which there is a compatibility relation across tasks (see also Koch & Prinz, 2002). Hence, forward crosstalk effects are not part of the stage-based dual-task models, but empirical evidence for such effects does not endanger the essence of the model.

Yet, there are also forms of crosstalk that are disallowed by the model, such as “backward compatibility” effects (BCE) from R2 to R1. A BCE should not occur because R2 selection cannot start before R1 selection has finished. However, many studies have observed BCEs (e.g., Ellenbogen & Meiran, 2008; Fischer, Gottschalk, & Dreisbach, 2014; Hommel, 1998; Janczyk, Pfister, Hommel, & Kunde, 2014; Lehle & Hübner, 2009; Lien & Proctor, 2000; Logan & Schulkind, 2000; Miller, 2006; for a review see Fischer & Plessow, 2015).

For example, Hommel (1998) used colored letters and asked the participants to first respond to letter color (T1) and then to letter identity (T2). Crosstalk effects on RT1 occurred when response codes for both tasks overlapped. More specifically, manual T1 responses to letter colors (e.g., red-left and green-right response) and verbal T2 responses to letter identity (e.g., saying “left” to an H and “right” to an S) produced substantial crosstalk (i.e., RT1 prolongation) when the verbal response “right” (vs. “left”) coincided with the left (right) manual response (spatial response-category mismatch) relative to when there was a response-category match across tasks. Later studies showed BCEs with various kinds of feature overlap (e.g., Ellenbogen & Meiran, 2008, 2011; Giammarco, Thomson, & Watter, 2015; Hommel & Eglau, 2002; Logan & Delheimer, 2001; Logan & Gordon, 2001; Logan & Schulkind, 2000; Miller, 2006), such as overlap at the level of spatial feature correspondence (e.g., Lien & Proctor, 2000), correspondence at the level of response execution vs. inhibition (i.e., if responding in the first task is delayed when the second task requires withholding a response; Miller, 2006), or correspondence at the level of T2 response force requirements and T1 response force (Miller & Alderton, 2006). Consistent with the idea of parallel response activation as basis for the BCE, Lien, Ruthruff, Hsieh, and Yu (2007) showed parallel motor response activation using EEG measures (the lateralized readiness potential, LRP). However, their data also showed that parallel response activation does not result in a performance benefit in response-congruent conditions relative to “no overlap” control conditions that do not enable a BCE, suggesting that parallel response activation is possible but not necessarily beneficial for performance. Such findings, together with a large number of related studies, suggest that S-R translation processes of T1 and T2 were not strictly serial but can actually proceed in parallel, particularly when the tasks are “similar,” such as when they share features on a common processing dimension (for a review see Fischer & Plessow, 2015).

At first sight, evidence for backward crosstalk in the PRP paradigm seems to be highly damaging to the notion of a structural central bottleneck because it suggests that features of the second response are activated before or while the first response is being selected, which challenges the idea that response selection operates strictly serially. To account for such BCEs, it has been suggested that the response-selection stage is subdivided in two phases. First, there is a response-activation phase that can run in parallel for both tasks, which is then followed by a strictly serial response-selection process. In this architecture, some R2-based priming of R1 response-code activation is possible, which should affect “final” R1 selection (e.g., Hommel, 1998; Lien & Proctor, 2002). Hence, this modification would rescue the serial character of response selection in the PRP paradigm, but the modified model would pay the price of higher complexity and a less identifiable distinction between response activation and response selection, which renders falsifiability of the theoretical “serial response selection core” of the original model much more difficult (see Janczyk, 2016, for a recent discussion).

Notably, many studies have started to identify the factors that determine the degree of parallel processing, as measured by the size of the BCE. For example, in the context of general considerations of cognitive control requirements, it has been argued that there is a control continuum ranging from a highly selective “shielding” mode, in which task sets are protected from interference from other tasks and response selection is serial, to a “shifting” mode, in which performance is less selective and flexible shifts to alternative tasks are facilitated. It has been argued that task-set shielding and shifting are two complementary requirements calling for adaptive control settings along this shielding-shifting “dilemma” (e.g., Goschke, 2013). Any factor that affects this control setting will also affect the degree to which between-task crosstalk effects occur. For example, Fischer et al. (2014) assessed the size of the BCE as marker for the prevalence of serial vs. parallel processing mode and introduced a location-dependent variation of proportion of incongruent trials. They found that participants learned to adjust their processing mode in a context-specific way, being more serial if a large proportion of incongruent trials was associated with a certain stimulus presentation location. Fischer and Plessow (2015) suggest that such a shift between parallel and serial processing modes can be taken as a marker of adaptive behavior.

Taken together, the empirical evidence suggests that serial processing is a mode that favors task-set shielding and that is often adopted in the context of “standard PRP experiments,” in which the task instruction emphasizes priority of T1 processing over T2 processing (see also Schumacher et al., 2001). However, more parallel processing is possible when being less strongly in the shielding mode, and in fact occurs regularly if it does not violate task instructions.

Higher-Level Executive Task-Order Control. The explanation of between-task crosstalk, and backward crosstalk specifically, invokes processes that change processing priorities along a shielding-shifting continuum. Yet, dual-task performance seems to be flexible both with respect to the degree of between-task capacity sharing and more generally in the setting up of the sequence in which the tasks are performed in the first place. The standard PRP paradigm instructs participants to perform T1 first. Because this order is fixed by instruction, the original central bottleneck model does not require additional assumptions as to how the instructed order is actually established. As flexible order is not within the bounds of the original PRP framework, flexible mechanisms of task-order scheduling are simply beyond the scope of the central bottleneck model. However, there is increasing evidence for such higher-level control mechanisms that flexibly exert task-order control.

The central bottleneck account suggests the simple idea of “first-come first-served” (resulting in “passive” queuing for access to the bottleneck) without involving additional mechanisms of response-order control. However, such a simple queuing mechanism would predict that a change in the order of stimulus presentation would also result in a change in the order of response selection for the two tasks, but this is not always observed. For example, Lien et al. (2008) found that the expected task order is often maintained even if S2 is presented prior to S1 (i.e., with a negative SOA), suggesting that participants prepare a specific processing order, and this preparation at the level of task order determines the order of response selection processes. Likewise, it has been argued that the PRP effect is at least partially due to incomplete preparation for T2 while performing T1 (e.g., De Jong, 1995; Gottsdanker, 1979). If so, increasing the SOA would provide participants with additional time for preparing for the upcoming task switch from T1 to T2, which should result in improved performance with longer SOAs, exactly as it is typically observed as PRP effect. Another way to reconstruct this account would be to argue that a task switch requires some task-set reconfiguration, and that this reconfiguration can start (or can be completed) only once the central process of response selection in T1 has been completed, and that the cognitive system cannot be configured for performing two tasks at the same time with the same efficiency as when performing only one task at a time. If so, task performance in dual tasks should always be less efficient than in a single-task condition because the preparatory state is less optimal. The finding of “task-set costs” in single-task trials that are unpredictably interspersed in dual-task trials (relative to “pure” single-task blocks) supports this idea that preparation and maintenance of two task sets comes with some costs (e.g., Schumacher et al., 2001). Consistent with this idea, many studies using the PRP paradigm observed “concurrence costs” (see, e.g., Logan & Gordon, 2001, for a review), indicating that T2 performance often does not reach single-task baseline even with long SOA. However, even more compelling evidence for the idea that tasks need to be prepared in the context of task pairs (e.g., dual tasks) comes from studies that manipulated task order.

Typically, the instructions used in PRP paradigms emphasize that responding to the first stimulus needs to occur before responding to the second stimulus. In line with the central bottleneck model, performance on T1 should be independent of the SOAs used between the two tasks and also independent of T2 performance, and studies have often not even reported T1 performance in detail (see Strobach et al., 2014, for a review). Yet, Strobach et al. (2014) analyzed the available data and found that more than half of these studies showed an increase either in RTs and/or errors in T1 for short SOAs, suggesting that T1 performance is not independent of SOA. Specifically, responses to the first task are often slowed down compared to when this task is executed in isolation (e.g., Jiang, Saxe, & Kanwisher, 2004; Sigman & Dehaene, 2006). Also, when the sequence of the two upcoming (dual) tasks is made unpredictable, T1 performance suffers (e.g., De Jong, 1995; Szameitat, Schubert, Müller, & von Cramon, 2002; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006; Sigman & Dehaene, 2006; Töllner, Strobach, Schubert, & Müller, 2012; see Schubert, 2008, for a review of such “executive” dual-task control processes).

Particularly the latter finding, that T1 performance suffers when the instructed order of the two tasks is variable, is an important finding. Luria and Meiran (2003) systematically manipulated task order in the PRP paradigm using an explicit instructional order cue and found that RT1 was increased when the order changed (e.g., from T1-T2 to T2-T1). Moreover, when the cuing interval was long, allowing for preparation of the new task order, the “order-switch costs” were reduced. In addition, they found that the PRP effect was increased in a task-order switch relative to a repetition. This suggests that processes of order control also affect those processes that cause the PRP effect. Specifically, the authors assumed that task order is represented as a higher-level “order set” (see also Szameitat et al., 2002; Szameitat et al., 2006).

Importantly, most studies on task order control varied repetition at the task-pair level and repetition of the individual tasks across task pairs inversely (see also Lien & Ruthruff, 2004, for a discussion), so that pair switches were associated with task repetitions across pair (e.g., from T1-T2 to *T2*-T1), while pair repetitions resulted in task switches across pairs (e.g., from T1-T2 to *T1*-T2). Recently, Hirsch, Nolden, and Koch (2017) devised a paradigm with more than two tasks, creating three different task pairs, so that the task transition across pair can be controlled (i.e., kept constant as a task switch) because either the second task is always the same (e.g., T2-T1 vs. T3-T1) or the first task (e.g., T1-T2 vs. T1-T3; see Hirsch, Nolden, Philipp, & Koch, 2017). These authors could confirm and extend previous findings of task-order switch costs.

Specifically, Luria and Meiran (2003) speculated that dual-task order control involves inhibition of the competing order set, even though direct evidence for such inhibition was not available at that time. With the paradigm introduced by Hirsch et al. (2017) it was possible to examine the potential influence of inhibition at the task-pair level. They examined whether performance would be impaired in a n-2 task-pair repetition relative to a n-2 task-pair switch. In studies on task switching, it has been found that n-2 repetitions produce performance costs, which have been attributed to persisting inhibition of tasks (n-2 repetition costs or “backward inhibition,” see Gade, Schuch, Druey, & Koch, 2014; Mayr & Keele, 2000; Koch et al., 2010, for reviews). Notably, Hirsch et al. (2017) found a performance *benefit* (rather than a cost) in n-2 pair repetitions, suggesting persisting activation at the level of task-pair representations and that inhibition of competing order sets is not the critical selection mechanism at the level of higher-order task control settings. Taken together with the finding of task-pair switch costs, there is converging evidence for higher-order control mechanisms that enable people to prepare and reconfigure task-control settings at the level of task pairs.

The existing evidence thus suggests that there are control mechanisms that allow flexible task orders, whereas early “structural bottleneck” models of the PRP paradigm were optimized to explain performance once a stable order set has been implemented. This implementation of an order set could be based on explicit instructions, like in Luria and Meiran’s (2003) and Hirsch et al.’s (2017) studies, but task order can also be “implicitly” suggested by factors that are intrinsic to task processing in dual tasks itself. For example, Ruiz Fernández, Leonhard, Rolke, and Ulrich (2011) showed that people may choose the order in which they process the two tasks depending on task difficulty. In their study, participants were presented with a tone and a letter (in random order) in a succession, with varying SOAs between tone and letter. The participants were asked to respond as quickly and as accurately as possible to both tasks, emphasizing that both tasks were equally important. The difficulty of the letter task was varied between first and second half of the experiment. In the easy condition, participants were asked to respond to each stimulus with a single key press (easy response condition) for both the tone and the letter task. In the difficult response condition, participants were asked to respond to the tone task with a single key press, but to the letter task with a more time-consuming key-press sequence. The results showed that participants tend to perform the tone task first more often when the response requirement for the letter task is hard rather than easy. This observation emphasizes the idea that participants flexibly adapt response scheduling in dual-task situations (see also Meyer & Kieras, 1997).

Flexibility in Task switching

In contrast to dual-task research, where the topic of flexibility only recently gained more interest, research on task switching has focussed on cognitive flexibility from early on.

Here we aim at pointing out commonalities in the research approaches and findings across both paradigms.

Note that switch costs represent a sequential measure that may also include some involuntary (i.e., “non-executive”) after-effects of previous control states (proactive task-set interference; see Allport et al., 1994). Therefore, the task-switching paradigm has been optimized to provide evidence for flexible “executive” control of tasks (see Monsell, 2003; Vandierendonck et al., 2010). In the next subsection, we review evidence for preparation effects as a hallmark of cognitive flexibility (i.e., “executive” control). Then we discuss mixing costs in task switching as evidence for lack of (full) preparation. Finally, we discuss “task-rule congruence effects” (i.e., crosstalk between task sets) as an implication of lack of full preparation as well as competing-task inhibition as mechanisms that enhance flexible moment-to-moment reconfiguration of task set.

Preparation Effects in Task Switching. A strong version of task-set reconfiguration would imply that a task switch requires a switch-specific reconfiguration process, but that some part of this reconfiguration can be achieved based on advance preparation (e.g., Mayr & Kliegl, 2003; Rogers & Monsell, 1995; Rubinstein et al., 2001; see Kiesel et al., 2010; Monsell, 2003; Vandierendonck et al., 2010, for reviews). The influence of preparation on the costs of task switching has received considerable research attention because it can be interpreted as reflecting cognitive flexibility in changing environmental contexts. In comparison, research on dual-task performance has been less focussed on such “executive” task-set reconfiguration processes (see Logan & Gordon, 2001; Meyer & Kieras, 1997; Schubert, 2008, for discussion), presumably because of the strong influence of the PRP framework, in which SOA effects are typically related, at a theoretical level, to response selection rather than to task selection (Pashler, 2000). In task switching, the primary method to examine preparation effects is to manipulate the time for an upcoming switch.

For example, Rogers and Monsell (1995) used predictable task sequences (AABB) and varied the response-stimulus interval (RSI). With predictable switches, the RSI can be taken as the time period during which participants could prepare for a switch. The authors indeed found that switch costs were reduced with longer RSI. In subsequent studies, preparation has often been examined using unpredictable task sequences in which each individual task is indicated by an explicit task cue (e.g., Meiran, 1996). In such studies, the cue-stimulus interval (CSI) corresponds to the time during which participants know the identity of the upcoming task and which could thus be used for active task preparation.[7] Numerous studies found that a longer CSI leads to general preparation benefits in both switch and repetition trials, and that often the switch costs are reduced by preparation (e.g., Hoffmann, Kiesel, & Sebald, 2003; Koch, 2001; Koch & Allport, 2006; Meiran, 1996; Monsell & Mizon, 2006). Notably, switch costs are usually reduced but not completely eliminated, so that some "residual" switch costs typically remain even after long preparation time (Kiesel et al., 2010, for a review). These residual switch costs have been discussed in terms of possible structural limitations of complete preparation, but the crucial aspect for the present purpose is that the preparatory reduction of switch costs has been taken as a primary index of advance reconfiguration, reflecting cognitive flexibility (Vandierendonck et al., 2010).

The empirical effects of CSI manipulations have led to various theoretical explanations. For example, it has been argued that preparation corresponds to the retrieval of a new task intention from memory, which is actually an all-or-none process (De Jong, 2000). If so, the probability of preparation simply increases with longer preparation intervals. Hence, in a block of trials, there would always be a mixture of fully prepared trials and completely unprepared trials. Notably, this account assumes that preparation corresponds to an all-or-

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[7] Please note that in the task-switching literature the term CSI is used to refer to the SOA between cue onset and stimulus (i.e., target) onset and could thus also be termed cue-target SOA. Note also that in the task-cuing paradigm, the CSI is usually varied in a way that keeps the RSI constant in order to control the influence of theoretically postulated processes of "decay" of task-set activation (e.g., Meiran, Chorev, & Sapir, 2000; but see Horoufchin, Philipp, & Koch, 2011, for a critical discussion of the empirical evidence for task-set decay).

none memory retrieval process that does or does not take place prior to the presentation of the target stimulus, which would explain both preparation effects and residual switch costs (see Lien, Ruthruff, Remington, & Johnston, 2005, for a discussion). Likewise, Altmann and Gray (2008) assume a similar all-or-none retrieval of "episodic task codes."

In contrast, other models assume at least tacitly a more gradual change of preparatory state within the time-course of a single trial. For example, Rogers and Monsell (1995) assumed that preparation takes place gradually but cannot be completed prior to target onset, so that some aspect of preparation, such as activation of the specific S-R rules of the new task, has to wait until being "exogenously" triggered by target stimulus itself (see also Mayr & Kliegl, 2000; Rubinstein et al., 2001). Similarly, Meiran et al. (2008) assumed a preparatory process of shifting attentional weights for stimulus interpretation (stimulus-set biasing), whereas changes in task-specific category-response associations and the corresponding response codes occur only retroactively, and this persistence of previous response codes might explain some of the residual switch costs particularly if tasks share sets of responses (see also Oberauer, Souza, Druey, & Gade, 2013).

Importantly, research on task preparation has led to a better understanding of the components underlying such effects. For example, Logan and Bundesen (2003; see also Mayr & Kliegl, 2003) used two cues for each of the two tasks and found that the switch costs were significantly reduced if a task repetition was indicated by the alternate cue for this task, suggesting some cue-repetition priming as a component of switch costs. Furthermore, they found that the influence of preparation time mainly affected this cue-switch component rather than the "true" task-switch costs (see also Koch, Lawo, Fels, & Vorländer, 2011). To explain their data, Logan and Bundesen (2003) proposed that participants form cue-target compounds that directly activate the responses that are associated with them. However, Monsell and Mizon (2006) demonstrated that a preparatory reduction of switch costs can occur if cue repetitions do not occur at all and if task switches are rare, and switch costs remain robust even if the cue-component is partialled out (e.g., when using so-called transition cues that indicate the transition rather than the identity of the next task itself, see Forstmann, Brass, & Koch, 2007, for discussion). Therefore, it has been suggested that cues activate verbal mediators (Arrington, Logan, & Schneider, 2007) or different retrieval paths to activate task sets (Mayr & Kliegl, 2003; see also Forrest, Monsell, & McLaren, 2014, for further discussion). Hence, cue priming represents an effect that contributes to switch costs (like other effects, such as congruence effects, see below) but the assumption of flexible switches between higher-level task representations (task sets) is still maintained by most researchers (see Jost et al., 2013).

However, just as preparation effects show the existence of cognitive flexibility in multitasking, they also highlight that preparation is often incomplete, which may reflect that preparation for one task also implies lack of preparation for any competing task, and that too strongly implemented task sets can actually be maladaptive if a sudden switch of tasks is necessitated (Goschke, 2013). Therefore, we now turn to a discussion of indirect effects of (lack of) preparation, which is shown in mixing costs and in congruence effects.

Mixing Costs and Constraints on Full Preparation. Importantly, many studies provided evidence suggesting that reconfiguration in task switching is not a strict all-or-none process (but see De Jong’s, 2000, “failure-to-engage” account; cf. Lien et al., 2005; see Kiesel et al., 2010, for review and discussion). If it was an all-or-none process, then a task repetition should result in an “optimal” task configuration that should equal that of a single-task condition. However, this is clearly not the case, as it is shown by mixing costs, which is measured as the performance costs in mixed-task conditions relative to single-task conditions (see Figure 1). Mixing costs are very robust, suggesting that repetition trials in mixed blocks do not represent a fully prepared baseline (similar to task-set costs in dual-tasks and concurrence costs in the PRP paradigm, see Logan & Gordon, 2001). Therefore, an important implication of mixing costs in task switching is that task preparation is typically not optimal even in task-repetition trials, presumably because the competing task set is still lingering in working memory and cannot be fully de-activated because it will be needed soon again. This idea of lingering task-set activation ("task set inertia," see Allport et al., 1994) implies that reconfiguration is not an all-or-none process (Longman, Lavric, Munteanu, & Monsell, 2014).

Accordingly, Meiran (2000) suggested that the system is biased to one or the other task, but that this biasing is a matter of degree (i.e., biasing is not perfect). More specifically, Meiran (2000) proposed "stimulus-set biasing" as a change of the attentional weighting of stimuli to favour the currently relevant stimulus features. However, stimulus-set biasing never reaches a 100% bias for a task, so that aspects of task performance that cannot be prepared in advance refer to the associative task-specific weights of the responses. These task-specific response codes result from a complementary process of "response-set biasing" that occurs as a by-product of task execution rather than as an additional control process (see also Meiran et al., 2008). Indeed, there is evidence that stimuli prime task-related response codes (e.g., Hsu & Waszak, 2012; Koch & Allport, 2006; Koch, Prinz, & Allport, 2005; Waszak, Hommel, & Allport, 2003) and such learnt stimulus-task and stimulus-response associations (or "bindings") are rather long-lasting and survive several dozens of trials (e.g., Moutsopoulou & Waszak, 2013; Pfeuffer, Moutsopoulou, Pfister, Waszak, & Kiesel, 2017).

The suggestion of graded stimulus-set biasing and reactivation of stimulus-task and stimulus-response associations resonates well with the idea that performance is driven by antagonistic processing constraints along a "task-set shielding vs. shifting" continuum (Goschke, 2013), which precludes overly strong task sets because this might be dysfunctional in case of situations that require an urgent shift of task. Notably, if a task is not fully prepared, some aspects of competing tasks might produce between-task crosstalk in task switching much like it has been found in dual-task research. In fact, such crosstalk is commonly observed in task switching and has been termed "congruence effects" (or task-rule congruence effect, see Meiran & Kessler, 2008).

Congruence Effects in Task Switching. Congruence effects can occur in task switching when stimuli and responses are “bivalent,” that is, contain features, or dimensions, that relate to different tasks. For example, Rogers and Monsell (1995) used digit-letter compound stimuli (e.g., G7), in which the digit referred to a parity judgment (odd vs. even), whereas the letter referred to a categorization into vowels and consonants and both tasks were responded to with the same left and right key presses. If the response to the task-irrelevant stimulus (or stimulus feature) does not correspond to the response required for the relevant stimulus feature (in case of an incongruent stimulus), then performance is worse than in case of correspondence (i.e., congruent stimulus). Such “congruence effects” have been reported early on in the literature on task switching (e.g., Meiran, 1996; Rogers & Monsell, 1995; Sudevan & Taylor, 1987). Congruence effects are usually large and robust when participants switch tasks (e.g., Fagot, 1994; Meiran, 2000), and they are often larger in switch trials than in repetition trials (e.g., Rogers & Monsell, 1995; Wendt & Kiesel, 2008; Wendt, Kiesel, Mathew, Luna-Rodriguez, & Jacobsen, 2013; see Kiesel et al., 2010, for a review).

With bivalent stimuli, task switching requires selective attention to select the task-relevant stimulus (or stimulus feature), but the task-irrelevant stimulus (feature) could still capture attention and activate the competing task and response. Kiesel, Kunde, and Hoffmann (2006) suggested that incongruent targets cause a response conflict because the target activates different responses according to the relevant versus irrelevant task rules. Interestingly, Liefooghe, Wenke, and De Houwer (2012) showed that congruence effects could even occur based on task instructions alone and thus do not require extensive S-R practice. This suggests that it is sufficient if participants form an effective representation of the different task rules in working memory, and that extensive practice of these rules is not necessary to yield congruence effects. Yet, Kiesel, Wendt, and Peters (2007) specified this effect by showing that congruence effects are not affected by the amount of concurrent memory load but by the frequency of specific S-R associations, suggesting that some proportion of the congruency effect stems from the development of direct S-R associations rather than from the activation of an abstract representation of the irrelevant task in working memory. Meiran and Kessler (2008) further suggested that congruence effects reflect activated overlearned response-category codes in long-term memory (see Schneider, 2015, for a discussion). That is, practice is apparently not necessary for congruence effects to occur, but practice enhances these effects. Correspondingly, Liefooghe et al. (2012) reasoned that the instruction-based task-rule congruence effect might occur only for simple task sets that represent a rather small number of S-R associations.

Forming task sets may help to shield the system from irrelevant information, so that switch costs can be interpreted as the consequence of successful shielding of the current task from the previous task (Dreisbach & Haider, 2008). Dreisbach and Haider (2009) showed that task representations, either in the form of a general task rule or based on practice, narrow the focus of attention and thereby prevent the cognitive system from processing any information that does not serve the current goal representation. Such an adaptive, context-sensitive change in attentional selectivity has already been proposed by Goschke (2000), who found that switch costs were larger after incongruent stimuli than after congruent stimuli. To account for this finding, he argued that an incongruent trial included more conflict, and to resolve this conflict, the currently irrelevant task has to be inhibited so that it is then harder to switch to this task. This idea resonates well with “conflict monitoring” accounts of cognitive control (Botvinick et al., 2001) and its application to sequential modulation of congruence effects in conflict tasks (e.g., flanker task, Simon task, Stroop task; see Abrahamse, Braem, Notebaert, & Verguts, 2016, for a recent review).

Interestingly, whereas congruence effects are usually larger in switch trials than in repetition trials, they are often not strongly (if at all) affected by task preparation (see Pashler, 2000). Hence, switch costs and congruence effects represent dissociable measures of task interference, differing to the degree to which they are affected by preparation. It is possible that task preparation with increased cuing interval refers primarily to the new task goal at a higher level (e.g., Rogers & Monsell, 1995; Rubinstein et al., 2001), but that subsequent changes of attentional selectivity (i.e., of the bias as implemented in the stimulus set) are rather sluggish, so that congruence effects are often not reduced by preparation. However, just like it has been shown in dual-task performance that task sets can be shielded against crosstalk when the experimental conditions favor a serial processing mode (e.g., Fischer & Plessow, 2015), it has been found that more “global” manipulations can also affect congruence effects. For example, Bugg and Braver (2016) found that the congruency effect was reduced in blocks with mostly incongruent trials relative to blocks with mostly congruent trials, suggesting a role for global attentional control processes in the task-rule congruence effect (see also Braverman & Meiran, 2015; Wendt, Luna-Rodriguez, Kiesel, & Jacobsen, 2013).

Task Flexibility and Task Inhibition. Such modulations of congruence effects in task switching appear to be analogous to those in dual-task performance, where it has been proposed that the degree of task shielding in dual-task processing is under attentional control based on probability of crosstalk (Fischer & Plessow, 2015). Notably, the processes underlying the resolution of processing conflict on incongruent trials have received comparatively little research in dual-task research, but in task switching it has been proposed that such conflict is resolved by inhibiting the competing task set. Inhibition is a mechanism that supports flexible switching between tasks and is typically seen as an “executive” process (Miyake , Friedman, Emerson, Witzki, Howerter, & Wager, 2000). We are not aware of systematic research on task inhibition in dual-task performance (with the exception of Hirsch et al., 2017, as mentioned earlier), but research on task switching has examined inhibitory processes at the task level in detail using the so-called n-2 repetition costs (“backward inhibition,” Mayr & Keele, 2000; see Gade et al., 2014; Koch et al., 2010, for reviews).

In the n-2 repetition paradigm, three different tasks are used (A, B, and C). The critical comparison refers to performance in a task switch depending on whether the task in trial n-2 is or is not repeated (i.e., ABA vs. CBA). Many studies found worse performance in n-2 repetitions. Because persisting activation of previously relevant task sets would predict a benefit of n-2 repetitions, n-2 repetition costs suggests persisting inhibition of previously abandoned task sets (see Koch et al., 2010, for a review). It is debatable whether inhibition represents a proactive control process occurring during task preparation (e.g., Kuhns, Lien, & Ruthruff, 2007) or a more reactive process occurring during task performance itself (e.g., based on conflict resolution during response selection; Philipp, Jolicoeur, Falkenstein, & Koch, 2007; Schuch & Koch, 2003), but there is little doubt that inhibition is a mechanism that supports flexible task switching from one trial to the next, despite its potentially adverse after-effects in case of n-2 repetitions (see, e.g., Grange, Kowalczyk, & O'Loughlin, 2017, for a recent discussion, and Sexton & Cooper, 2016, for a computational modelling account).

At this point it is interesting to compare the role of inhibition in task switching and in dual-task performance. In task switching, inhibition is a major research topic and a substantial body of evidence has amassed indicating that inhibition occurs when switching tasks. In contrast, the idea that shifting from T1 to T2 in a dual-task trial requires active inhibition of T1 is usually not entertained. This is probably due to the prevalence of the structural research perspective in dual-task research, in which it is assumed that sequencing of the two component tasks is governed by a passive queuing mechanism rather than by an active and flexible scheduling mechanism (see Meyer & Kieras, 1997; Pashler, 1994; Schubert, 2008, for discussion). However, even crosstalk accounts that focus on between-task congruence effects in dual-task performance usually do not discuss the nature of the congruence effects in terms of whether resolution of incongruence requires inhibition of the competing response or competing task or whether it requires increased activation of the relevant response. Possibly, the lack of an unequivocal empirical marker for inhibition in dual-task performance is responsible for this research gap. Interestingly, in the context of flexible higher-level control of task order in dual tasks, Hirsch et al. (2017) used the n-2 repetition logic at the level of task pairs (using three different pairs of tasks) and did not find any evidence for inhibition as a mechanism underlying task-order control in dual-task performance. Thus, the present review highlights this issue as lacking further research.

Integrative Summary

In this section, we have discussed empirical evidence for cognitive flexibility in multitasking. There are two major lines of research. First, there is evidence for the flexibility of the processing mode with respect to task-set shielding, which is primarily based on studies assessing between-task crosstalk (i.e., congruence effects) and which is a relevant research topic in dual-task and task-switching research alike. Arguably, between-task crosstalk can occur only to the extent to which task-set selection is incomplete, so that crosstalk effects represent a side effect of cognitive flexibility because a complete and exclusive cognitive reconfiguration towards performing just a single task would result in dysfunctional rigidity and the inability to shift mental sets (cf. Schultz & Searleman, 2002; corresponding to clinical phenomena of task perseverance; see, e.g., Poljac & Bekkering, 2012; Watkins, 2008, for reviews). Interestingly, research in task switching has shown that inhibition of competing tasks (measured as n-2 task repetition costs) is a mechanism that may reduce between-task crosstalk. In contrast, task inhibition is no major explanatory concept in dual-task research, presumably because it is methodologically difficult to assess suitable empirical markers (see Hirsch et al., 2017, for a discussion).

Second, there is ample empirical evidence from studies on active task preparation, which is, like task inhibition, more difficult to investigate in dual-task studies but represents a major focus in task switching. Generally, these studies suggest that lack of full preparation, and, correspondingly, incomplete task selection is responsible for substantial interference in multitasking. The notion that there is variation in the degree to which task sets are prepared implies that there must be both contextual and top-down variables that affect whether participants perform individual tasks in multitasking more in a shielding mode (serial processing) or a shifting mode (parallel processing). The present review showed that the issue of flexibility in the selection of the most appropriate processing mode has recently become an increasingly dominant theme in dual-task research, which is mirrored in research on task switching on the factors modulating between-task congruence and inhibition effects.

Cognitive Plasticity Perspective on Multitasking

Flexibility refers to the short-term adaptation of the cognitive system to optimize task performance in a given situation, such as short-term changes in the degree to which task sets are selected, activated, and shielded from interference. However, practicing multitasking over a larger time range, from several experimental trials to days, weeks, months, or years of practice may also lead to more long-term changes in the organization of cognitive (and neuronal) processes. Such long-term changes refer to the plasticity of the underlying processes. A minimal definition of plasticity refers to long-term changes of performance with practice, but a stronger definition of plasticity would imply an experience-dependent qualitative change in the organization of the underlying task processes. Generally, with plasticity we refer to the potential modifiability of cognitive processes as a function of practice (Karbach & Schubert, 2013). There is an increasing number of studies that explored practice effects in both dual-task and task switching performance.[8]

Practice Effects in Dual-Task Performance

The study of practice effects on divided attention has a long tradition based on using continuous tasks. However, as we have argued earlier, such tasks allow little experimental control of the timing of the component processes. Therefore, when using combinations of

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[8] We would like to note that developmental change across the lifetime also represents an example of cognitive plasticity (e.g., Lövdén et al., 2010). Generally, cognitive abilities develop over time, so that multitasking performance is increasing over the childhood and reaches an optimum in young adults, but there is some age-related decrease of performance in older people (for more recent reviews and meta-analyses see, e.g., Kramer & Madden, 2008; Kray & Ferdinand, 2014; Verhaeghen, 2011; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). However, reviewing the developmental literature in more detail would be beyond the scope of the present review, so that we focus on experimental work that examined the influence of practice on multitasking performance.

continuous tasks, it is possible that practice leads to skilled coordination and fast switches between the component sub-processes, so that massive improvement of performance is possible even though the basic cognitive architecture stills maintains serial processing at critical central stages. If so, practice would seemingly lead to divided attention, whereas there is, strictly speaking, no division of attention at all but only improved task scheduling and rapid task switching. Therefore, in the present article, we primarily focus on RT tasks.

Task scheduling is an important executive control mechanism, but its examination has receded in the background when the PRP paradigm has become dominant in the study of dual-task performance in the mid-1980’s. In addition, the logic of the PRP paradigm requires using discrete RT tasks, so that the locus-of-slack logic could be successfully applied (e.g., Pashler, 1994). Such RT tasks seem to leave less room for task scheduling. Therefore, based on research using the PRP paradigm, it has become a strong theoretical claim that persisting dual-task interference is due to a structural processing bottleneck at central stages of decision and response selection (Pashler, 1994). However, two strands of research challenged this strong position. One refers to the study of between-task crosstalk effects (e.g., backward compatibility effects; see Janczyk, 2016, for a recent discussion), which we have described earlier. The other refers to the influence of practice effects because it should not be possible to eliminate a structural bottleneck based on practice. Hence, the study of dual-task practice effects represents the plasticity counterpart to the structural perspective.

Based on theoretical accounts assuming the existence of massive parallel processing (Meyer & Kieras, 1997), Schumacher et al. (2001) reported a dual-task study in which special conditions were met. For example, based on the argument that serial stimulus presentation also induces serial processing as a strategy, the stimuli were presented simultaneously. Moreover, typical instructions in PRP studies give one task priority (hence it is called T1), so that the order of task processing is predetermined, which again induces a serial strategy.

Therefore, Schumacher et al.'s (2001) instructions suggested performing both tasks at once. Using this paradigm, they found that dual-task costs (i.e., dual-task vs. single-task comparison) were basically eliminated, at least for some participants, after five sessions of dual-task training. This finding suggests that the central bottleneck is not structurally implemented but could be eliminated based on the plasticity of the cognitive system. Subsequent studies were able to replicate this reduction or possibly elimination of the dual-task costs under slightly different conditions (e.g., Hazeltine, Teague, & Ivry, 2002; see Schubert, Strobach, & Karbach, 2014; Strobach & Schubert, 2017a, for recent reviews).

Importantly, there seem to be limits to practice-based demonstrations of plasticity. Massive dual-task practice effects can be achieved using a visual-manual task combined with an auditory-vocal task, but these effects were weakened when different modality pairings were used, such as visual-vocal tasks combined with auditory-manual tasks (e.g., Göthe et al., 2016; Hazeltine et al., 2006; Levy & Pashler, 2001; Liepelt, Fischer, et al., 2011; Liepelt, Strobach, Frensch, & Schubert, 2011; Stelzel, Schumacher, Schubert, & D'Esposito, 2006). Hence, modality-specific factors may produce dual-task crosstalk that cannot be fully overcome by practice, and optimal practice effects are achieved only when so-called "standard" S-R modality pairings were used. Hazeltine et al. (2006) suggested a "natural tendency" to bind visual stimuli to manual responses and auditory stimulus to vocal responses, which might be the basis for optimal dual-task practice effects. More specifically, Stephan and Koch (2010, 2011, 2015, 2016) suggested, in the context of task switching, that the modality of the most dominant anticipated response effect (e.g., auditory effect of vocal response) defines the most compatible stimulus modality for this response ("modality compatibility") based on long-term "ideomotor" response-effect learning as a basic mechanism of action control (see also Badets et al., 2016; Greenwald, 1970; Hommel et al., 2001; Shin et al., 2010; for reviews).

Similar practice-based reductions of dual-task interference have been observed for the PRP effect, even though the reductions were usually less complete, presumably because the condition of simultaneous stimulus presentation is not met (Schumacher et al., 2001). Notably, early studies of practice effects in the PRP paradigm found only little impact on the PRP effect (e.g., Karlin & Kestenbaum, 1968), but such studies did not thoroughly separate the input and output modalities across tasks, suggesting that perceptual or motor interference might have played a role in these studies. The results from studies that accounted for such perceptual interference showed a different pattern. For example, Van Selst et al. (1999) and Ruthruff, Pashler, and Klaassen (2001) showed that the PRP effect is substantially reduced albeit not entirely eliminated with substantial practice (see also, e.g., Allen, Lien, Ruthruff, & Voss, 2014; Maquestiaux, Hartley, & Bertsch, 2004; Maquestiaux, Laguë-Beauvais, Ruthruff, & Bherer, 2008). Moreover, it has been shown that S-R modality mappings determine the degree to which the PRP effect decreases with practice, showing much larger reductions with standard mappings (e.g., Göthe et al., 2016; Hazeltine & Ruthruff, 2006).

However, a particular version of standard S-R pairings not only establishes “modality compatibility” but also “ideomotor compatibility,” such as when intended features of the response effect are maximally similar to the relevant features of the stimulus, which would be, for example, the case if one responds by saying “one” to hearing the stimulus ONE. Using ideomotor compatible tasks, Greenwald and Shulman (1973) showed that the PRP effect is more or less eliminated relative to using non-ideomotor compatible tasks. Despite some controversy (e.g., Lien et al., 2002) such effects of ideomotor compatibility on the PRP effect are quite robust (see, e.g., Halvorson & Hazeltine, 2015; Hartley et al., 2015).

If we just consider the overall reduction of dual-task interference and disregard the thorny methodological issue of demonstrating the non-existence of something (i.e., the elimination of dual-task effects), then the most relevant question is how exactly this reduction can be functionally explained. Ruthruff, Van Selst, Johnston, and Remington (2006) discussed three mechanisms that could potentially explain such practice effects.

One mechanism might refer to *task integration* (or task coordination), so that the processes of performing the two initially separate tasks become intertwined in a way that allow them to be performed conjointly (and hence eliminate the dual-task bottleneck). This task-integration learning could take place only with dual-task practice but not with practicing the component tasks in single-task sessions.

A second mechanism could be based on *task automatization*, suggesting that practicing a task automatizes the component processes, so that they are no longer capacity-limited and thus no longer compete for the central bottleneck. Task automatization should be possible even with single-task practice. Both task integration and task automatization would reflect cognitive plasticity in terms of a functional change in the underlying mechanisms.

Finally, there is also the third possibility, that practice shortens the time for each component process ("stage shortening"), so that performance is generally improved, but that there is *no qualitative change* in the underlying cognitive architecture. Notably, even such an account could explain the elimination of dual-task costs while maintaining the existence of a central bottleneck by assuming that practice has shortened the central processing stage to a degree that response selection in T1 is always completed (even at very short SOA) before the critical response-selection stage in T2 is required. This idea has been termed "latent bottleneck" (e.g., Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003).

Ruthruff et al. (2006) argued that the existing evidence is generally consistent with the "no qualitative change" account in terms of stage shortening, but that there is also evidence for task automatization, which implies a stronger degree of plasticity. However, recently Strobach and Schubert (2017b) found that even those participants who showed a practice-related elimination of dual-task costs are unlikely to have automatized processing and argued for a central stage shortening that results in the central bottleneck becoming latent rather than eliminated (Ruthruff et al., 2003). Based on a recent review of dual-task practice studies, Strobach and Schubert (2017a) concluded that practice-related benefits mostly refer to the central processing stage and much less (if at all) to basic perceptual or motor processes.

In addition to practice benefits for the component task processes (primarily at the central stage), there is also more recent evidence for task integration in terms of executive task coordination. For example, Liepelt et al. (2011) showed that dual-task practice resulted in much stronger practice benefits than single-task practice, even though the component tasks themselves have been practiced to an equal degree in both conditions, which suggests the acquisition of more general dual-task integration and executive coordination skills, such as shortened time for task-switching operations in dual tasks (see Strobach et al., 2014; Strobach & Schubert, 2017a, for discussion).

Taken together, recent studies showed strong evidence for practice-based reductions of dual-task costs both in the classic dual-task paradigm and the PRP paradigm. However, this research has also pointed out clear limitations of practice benefits, such as interference with shared stimulus and response modality, but also modality-specific S-R mapping influences that go beyond simple perceptual or motor interference (e.g., stimulus masking or bimanual motor crosstalk) and suggest structural crosstalk based on inevitable processes of response-effect anticipation (Hazeltine et al., 2006; Stephan & Koch, 2011). Yet, practice benefits can be massive. Task automatization, general speed-up without qualitative change in processing, and task coordination are not mutually exclusive accounts, so that each mechanism could contribute to practice benefits, depending on the specific experimental conditions.

The issue of practice-related benefits in executive task coordination raises another issue. Beyond the questions of whether there are practice gains in the practiced task and how these gains can be explained, the plasticity issue is also at the heart of recent attempts at designing specific practice schedules that might be effective as intervention strategy to improve other cognitive abilities or at least compensate declining cognitive abilities (e.g., Strobach & Karbach, 2016). This is the issue of transfer of practice. For example, in their study, Liepelt et al. (2011) found that practice benefits also transferred to changed task requirements. Interestingly, based on earlier findings of beneficial effects of action video games that require a strong degree of concurrent processing (i.e., multitasking) on aspects of selective attention (Green & Bavelier, 2003), it has recently been found that dual-task performance can be improved by such games (e.g., Anguera et al., 2013; Chiappe, Conger, Liao, Caldwell, & Vu, 2012; Strobach, Frensch, & Schubert, 2012). That is, practicing dual tasks in a simulated “real-world scenario” can improve dual-task performance in highly controlled laboratory settings. However, the degree to which such transfer of dual-task practice is near or far still represents a matter of debate (see Green & Bavelier, 2012; Strobach & Karbach, 2016).

The issue of transfer of practice has also inspired research on motor control, where the issue of transfer of practice is an important applied research topic (e.g., Rosenbaum, 2009; Schmidt & Lee, 2011). In this research, the issue of age-related impairments in divided attention generally (e.g., Kramer & Madden, 2008, for a review) and dual-task performance specifically (see Verhaeghen et al., 2003, for review and meta-analysis) has received increasing interest in the movement sciences (see Woollacott & Shumway-Cook, 2002, for a review). It is now widely acknowledged that there are close links between age-related cognitive changes and changes in motor control (see, e.g., Montero-Odasso, Verghese, Beauchet, & Hausdorff, 2012). Motor control of complex movements, with prime examples referring to gait and postural control, are characterized by a number of kinematic features, such as movement amplitude, velocity, and trajectory. For example, Krampe, Schaefer, Lindenberger, and Baltes (2011) found that a concurrent memory search task (generating exemplars of a predefined category) produced clear dual-task costs in the distances walked during the allotted time, and these costs were larger in older than in young adults. Obviously, walking is a fairly complex and continuous motor control task, but other studies also used less complex, more static postural control tasks, such as standing on a balance platform, and found similar age-related performance decline (for reviews see, e.g., Beurskens & Bock, 2012). Boisgontier et al. (2013) suggested that performing postural tasks becomes less automatic with age, so that such tasks require increased allocation of attentional resources, which in turn can produce increased dual-task costs.

However, if changes in attentional and motor control are interrelated, practice regimes that improve cognitive processes could possibly also transfer to improve motor functioning. That is, motor impairment might be compensated by increased engagement of cognitive processes, which in turn might be improved by cognitive practice. Such a compensation in terms of changed organization of sensorimotor control would be a good example of cognitive plasticity (see Beurskens & Bock, 2012). The evidence suggests some benefits of a dual-task intervention to improve motor performance in older adults for a variety of motor outcome measures (see Pichierri, Wolf, Murer, & de Bruin, 2011, for a review; Wang, Pi, Chen, Liu, Wang, & Chan, 2015, for a meta-analysis based on 27 studies). Yet, Wollesen and Voelcker-Rehage (2014) noted that, even though most studies found practice effects in the practiced tasks themselves, evidence for far transfer to everyday motor tasks is still scarce.[9]

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[9] As we have described earlier, the use of continuous tasks is a potential impediment for developing specific theoretical accounts that go beyond general resource ideas. Moreover, when considering this type of research on cognitive practice using cognitive-motor dual tasks, a great diversity of continuous motor tasks (e.g., postural control on a balance board) and outcome measures were used. However, methodological and technological improvements may help to segment complex and continuous movement sequences in smaller units, so that time-locked analyses are possible and "PRP-like" experimental designs feasible. Arguably, such designs allow a better and more fine-grained temporal analysis of multitasking interference, which seems critical for further theoretical development and a better confluence of research on cognitive and motor aspects of dual-task practice.

In summary, there is a growing literature on practice effects in dual-task performance. This literature reveals substantial practice benefits both on dual-task costs and on the PRP effect. The notion of a structural central bottleneck can explain some of these effects (based on the idea of the bottleneck becoming “latent” based on stage shortening (e.g., Ruthruff et al., 2003; Strobach & Schubert, 2017b), but other findings seem to speak in favour of executive task coordination skills that are acquired during dual-task practice. We have discussed such findings already in the section on cognitive flexibility, so that it seems only natural that studies on plasticity in multitasking reveal that such mechanisms that enable cognitive flexibility are also those that can benefit from practice. A parallel literature on practice effects is also developing in the area of task switching, to which we turn next.

Practice Effects in Task Switching

Probably the earliest demonstration of practice effects in task switching were reported by Rogers and Monsell (1995, Experiment 1). They had participants perform task switching with predictable double alternation of tasks (e.g., AABB) over two sessions, on two separate days, and found that switch costs decreased from 262 ms on the first day to 186 ms on the second day. Moreover, Koch (2001, Experiment 1) had participants practice a nine-element sequence of three different tasks in a cued switching paradigm over ten blocks of 72 trials each (i.e., the task sequence was repeated eight times in each block). Sequence-specific learning was assessed by presenting the same tasks in a new sequence in a ninth block testing negative transfer. Notwithstanding the observed sequence-specific learning effect (see also Gotler, Meiran, & Tzelgov, 2003; Heuer, Schmidtke, & Kleinsorge, 2001; Koch, Philipp, & Gade, 2006), switch costs were 284 ms in the first block but decreased to 143 ms already in the fifth practice block, after which switch costs stabilized and remained more or less constant. Hence, these data show that relatively little practice leads to a sizeable reduction of switch costs. However, with this little or moderate practice, switch costs by no means disappeared. Later studies have tested whether extended practice can eliminate switch costs.

For example, Cepeda, Kramer, and Gonzalez de Sather (2001) used three practice sessions and Kray and Lindenberger (2000) used even eight sessions and likewise found strong reductions of switch costs and mixing costs with practice, but there remained substantial costs at the end of practice. Using extensive practice, Berryhill and Hughes (2009) still found apparently irreducible residual switch costs of about 20 ms. Likewise, Stoet and Snyder (2007) had four participants practice task switching for more than 23,000 trials and still found significant switch costs ranging from 20 ms to 113 ms across the four participants. This difficulty in finding a complete elimination of switch costs by practice is confirmed by Strobach, Liepelt, Schubert, and Kiesel (2012), who reported small but still significant switch costs of around 10 ms after eight practice sessions (together including more than 7,000 trials). Interestingly, these authors found that mixing costs were in fact eliminated, but the tasks used in this study differed in stimulus modality (a visual task with three horizontal stimulus locations spatially mapped to three left to right ordered response keys and an auditory task with stimulus pitch mapped to responses in a compatible, rule-like manner), so that mixing costs were not significant from the outset and also switch costs were very small (about 25 ms) already in the first session.

Thus, the specifics of the experimental paradigm may determine the overall size of costs in task switching and thus the level to which these can be reduced by practice, but the general conclusion of these studies is that the costs of task switching are highly persistent. Therefore, unlike the debate in dual-task research, where the issue of elimination of dual-task costs has been debated quite fiercely because of its apparent implication for the existence of a structural bottleneck (see Ruthruff et al., 2006, for a discussion), the issue of elimination of switch costs has not been in the focus of the study of practice effects in task switching. Instead, the issue of transfer of practice has received more interest.

Some of the studies on practice effects were explicitly interested in transfer effects, that is, whether practice benefits would transfer to other, non-trained skills. For example, Minear and Shah (2008) used a pretest-posttest design and examined whether training with a pair of tasks would be beneficial if the practice effect is assessed with a different (but similar) pair of tasks. This would be an example of so-called near transfer. They trained three different groups of participants. One group practiced predictable task switches (i.e., AABB), another group unpredictable but pre-cued task switches, and a final group had single-task practice only. Note that there were practice benefits at posttest in all groups, showing near transfer. Importantly, only mixing costs showed larger transfer effects for task-switching practice relative to single-task practice in the control group. This indicated that near transfer was larger when switching itself and not only performing the constituent tasks was trained. However, there were no specific effects of task-switching practice on switch costs.

A study by Karbach and Kray (2009) also found near transfer of switching practice on mixing costs, but this study also showed transfer effects on switch costs. This study had a developmental focus, comparing performance of children (mean age = 9 years), young adults (mean age = 22 years), and older adults (mean age = 69 years). The three age groups were subdivided into further subgroups that differed in their practice schedule, including a single-task group and different task-switching groups. All participants underwent pretesting and posttesting with an extensive battery of cognitive performance tests, such as the Stroop task, verbal and spatial working memory, and fluid intelligence. The main findings were that, generally, both mixing costs and switch costs were increased in children and older adults relative to young adults, and that there were considerable practice benefits in all groups. Specifically, however, task-switching practice resulted in larger benefits than single-task practice. This suggests that participants had acquired a specific skill in coordinating task performance in task switching in addition to optimizing individual task performance as shown by the practice benefits after single-task training (see also Zinke, Einert, Pfennig, & Kliegel, 2012). This finding resonates well with studies on dual-task practice that suggested the acquisition of executive coordination skills in terms of improved task-switching operations (Strobach et al., 2014; Strobach & Schubert, 2017a, for review and discussion).

Notably, an important implication of the findings of transfer of task-switching practice is that they suggest that general "executive" processes of cognitive control of task coordination can be improved, so that it can be transferred even to somewhat different instantiations of the same tasks (e.g., near transfer, see also Minear & Shah, 2008). However, even more important is that Karbach and Kray (2009) also found evidence for far transfer, that is, transfer to very different tasks that still require executive control processes that have putatively been trained. Specifically, these authors found that performance in the Stroop task, in spatial and verbal working memory, and even in a test of fluid intelligence, improved in the posttest, and this improvement was larger in the task-switching groups than in the single-task group, indicating "far" transfer. This far transfer could be found in all three age groups to a similar degree. Such far transfer as a function of task-switching practice clearly holds the promise of applying task switching as a cognitive intervention (e.g., Kray, Karbach, Haenig, & Freitag, 2012, for an application to transfer of practice in children with attention deficit/-hyperactivity disorder; see also Strobach & Karbach, 2016, for a recent overview).

However, we would like to indicate that the area of cognitive practice is a rapidly growing research area that has produced highly promising but also controversial findings. To note but one example, it has been reported that a very taxing working memory training combining two so-called n-back tasks can result in increased fluid intelligence (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). This is clearly an example of far transfer, and the findings described above reported by Karbach and Kray (2009) are consistent with such far transfer. However, there is an ongoing controversy about the robustness of such findings and methodological intricacies implied in designing such studies (e.g., Shipstead, Redick, & Engle, 2012; see also Karbach & Verhaeghen, 2014, for a meta-analysis of working-memory training studies that revealed successful near and far transfer of training). This discussion is beyond the scope of the present review. In particular, this specific literature focuses on working memory training, in which multitasking requirements, if present, do not imply the stronger motor control requirements that are in the focus of the present article.[10]

In summary, studies on practice effects in task switching that report near transfer indicate that processes related to flexibly switching between tasks can be efficiently practiced. In contrast, evidence regarding far transfer of practice is more diverse, and it is currently an open question as to which practice regimes are suitable to practice general executive functions.

Summary and Conclusion

In our review, we organized experimental research on multitasking according to three complementary research perspectives: cognitive structure, flexibility, and plasticity. Notably, as we have elaborated in the preceding discussion, research on dual-task performance and on task switching differs in the strengths of their roots in the three research perspectives.

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[10] Finally, we note that a different but somewhat related case of far transfer of (life-long) training is currently discussed in the area of bilingualism research. It is argued that bilingual speakers practice language switching and presumably inhibition as a specific executive function to suppress the currently unwanted language (e.g., Meuter & Allport, 1999; see Declerck & Philipp, 2015, for a review of language switching). If so, practicing language control in the context of bilingualism might confer bilingual speakers a special bilingual advantage also in other (non-linguistic) domains that require cognitive control (see, e.g., Bialystok, 2017, for a review). However, again there is controversy about the robustness of the findings and the conditions under which they might be observed (see, e.g., Paap & Greenberg, 2013; von Bastian, Souza, & Gade, 2016, for critical discussions). Therefore, we leave it here by simply mentioning this debate about potentially beneficial effects of bilingualism.

Early dual-task research has been inspired by the “single-channel” metaphor of early information processing accounts (Broadbent, 1958). Based on this tradition, cognitive science has searched for the functional locus of a structural bottleneck in terms of a critical, capacity-limited processing stage in the cognitive system (e.g., Marois & Ivanoff, 2005; Pashler, 1994, for reviews). Yet, there were also about two decades (perhaps until the 1980’s) of intensive dual-task research on cognitive flexibility that was based on the concept of mental resources (e.g., Kahneman, 1973; Navon & Gopher, 1979). In this tradition, flexible trade-offs of typically quite complex and continuous tasks (e.g., reciting prose, sight-reading piano playing, etc.) have been examined, and the number of postulated resources has increased from a general resource to multiple, modality-specific resources (Wickens, 1984). The basic idea was that dual-task performance degrades to the degree the two tasks need to share a common capacity-limited resource. Notably, this kind of dual-task research combined the structural and the flexibility perspective by assuming both structural constraints (e.g., capacity limits) and flexible adaptation to task requirements. Yet, this kind of research approach has been largely overshadowed by the PRP paradigm combined with an approach that focuses on structural issues in terms of identifying critical processing stages in RT tasks (see Pashler, 1994).

The PRP paradigm has focused on discrete RT tasks and emphasized task instructions that were intended to exclude any flexibility, such as giving priority to one of two tasks (see Schumacher et al., 2001, for criticism). Hence, cognitive science has taken a direction into abandoning complex motor tasks in dual-task research in favor of using instead much simpler tasks to attain better experimental control over the timing of the component task processes. That is, the idea of identifying specific processing stages as functional bottleneck has come to be a heuristically highly successful research approach, applying mental chronometry to dual-task performance (e.g., Pashler & Johnston, 1989; Sanders, 1998; Sternberg, 1969).

Moreover, more recent research on practice effects in dual tasks had been motivated primarily by the structural stage logic, investigating whether practice refers to stage shortening (or even elimination). Importantly, such studies provided evidence for the acquisition of executive task coordination skills that go beyond the stage concept as embodied in the central bottleneck model (Strobach & Schubert, 2017a). Such practice effects, along with findings on the BCE (e.g., Fischer & Plessow, 2015) and dual-task order control (e.g., Hirsch et al., 2017; Luria & Meiran, 2003; Schubert, 2008) demonstrate much larger cognitive flexibility and plasticity of human multitasking than envisaged by the central bottleneck model. That is, the remarkable success of the central bottleneck model has been bought by a limitation in theoretical and explanatory focus, because the boundary conditions for its application are limited to specific experimental conditions (i.e., variants of the PRP paradigm). Specifically, the bottleneck model, taking on a structural perspective on cognitive architecture, depicts processing in multitasking situations essentially as two completely non-overlapping processing streams. That is, it was developed to explain multitasking interference in tasks without modality overlap at stimulus and response level, and, in addition, the tasks must not share codes in order to avoid content-based crosstalk. Furthermore, the central bottleneck model can be applied (with huge success) mainly for conditions in which two tasks are performed strictly sequentially (e.g., Miller & Ulrich, 2008, for a discussion of response grouping). Therefore, the notion of a central bottleneck represents an important idea in providing a general heuristic for explaining performance costs of multitasking in a variety of settings. Yet, the more recent evidence of the last 15 years strongly suggests that the idea of a structural central bottleneck needs to be complemented by theoretical concepts that go beyond the structural perspective and that take the complementary perspectives of cognitive flexibility and plasticity more strongly into account.

In comparison to research on dual-task interference, research on task switching was developed to focus on cognitive flexibility, but it has inherited the idea of a serial reconfiguration stage from the structural perspective on multitasking. Specifically, the idea that an active, "executive" control process of shifting a mental task set needs to be accomplished before the new task can be performed represents a very strong structural assumption. Given this structural constraint, however, active preparation endows the cognitive system with sufficient flexibility to deal with changing task requirements in a task switch.

Consequently, in task switching research, it has become an important research question to examine whether it is possible to reduce or eliminate switch costs by preparation, or if a residual cost will always remain because of a structural task-set reconfiguration bottleneck (Monsell, 2003, for a discussion). This is a very similar approach as the one in dual-task research, exploring whether it is possible to eliminate the serial response-selection bottleneck. Yet, even though it might be possible to see task-set reconfiguration as a separate processing stage, task-switching research has not explicitly focussed on this structural view and emphasized instead the flexibility and dynamics of task set rather than to declare reconfiguration as a "critical processing stage."

Such a theoretical perspective on reconfiguration suggests conceptualizing reconfiguration not abstractly as a central, capacity-limited stage but instead as a functional remapping mechanism that adaptively changes the task-specific connections (or short-term bindings) between relevant codes and categories in working memory. For example, recently, Oberauer et al. (2013) proposed that task sets can be modelled as a set of dynamic binding processes that connect various task elements in procedural working memory. These authors defined task set as "a set of mutually exclusive condition specifications, each of which is bound to one of a set of actions, which in turn are bound to (expected) outcomes" (p. 160). Moreover, their model assumes that there are analogous selection mechanisms both for items in declarative working memory and for actions in procedural working memory, which they call the “bridge” (i.e., their specific term for “task set”). Oberauer et al.’s (2013) mathematical model assumes that task-specific S-R links are represented as a matrix of bindings that is updated in each trial, which in turn draws on the pre-activated content of long-term memory. Updating and shifting of the bindings defined by the current task set thus corresponds to the actual mechanism underlying the cognitive reconfiguration, and it interacts with association learning that can strengthen both content in long-term memory and the bindings in working memory (i.e., task set).

Under this perspective, switch costs arise primarily because of both, the need to overcome memory-based interference referring back to the previous task (e.g., Allport et al., 1994; Waszak, Hommel, & Allport, 2003) and to executive processes that update task-specific bindings in working memory. Such a functional remapping account emphasizes the dynamic and adaptive aspect of human cognition and action (see also Altmann & Gray, 2008; Grange & Houghton, 2014; Schneider & Logan, 2005, 2014, for further discussions of computational models). Notably, compared to traditional stage models of multitasking, such functional accounts relate more closely to the actual mechanisms of action control and learning and can thus explain content-based interference phenomena such as modulations of switch costs and between-task crosstalk very naturally.

However, it is important to keep in mind that structure, flexibility, and plasticity are not mutually exclusive aspects of human behaviour but complement each other. Thinking in terms of abstract processing stages, which are defined independently of the type of content they process, is conducive to searching for structural bottlenecks but does not offer definitions of the representations and mechanisms underlying flexible moment-to-moment interactions across tasks and plastic changes in performance as a function of practice. Obviously, such mechanisms can be supplanted on bottleneck approaches, but it is important to keep in mind that such adaptive mechanisms are beyond the scope of structural bottleneck approaches.

The point of departure for our review was the diagnosis that research on dual-task performance and on task switching proceeded largely independently from each other, constituting separate traditions in the field of human multitasking. By organizing this field according to different research perspectives (i.e., cognitive structure, flexibility, & plasticity), we were able to discuss similarities and parallel development of empirical methodology and theoretical ideas across these paradigms. This integrative account has revealed that there is already considerable cross-fertilization. With our review article we aimed at highlighting the value of such an integrative position that goes beyond isolated consideration of a single theoretical research perspective and that broadens the focus from single experimental paradigms and emphasizes instead the fundamental similarity across multitasking paradigms.

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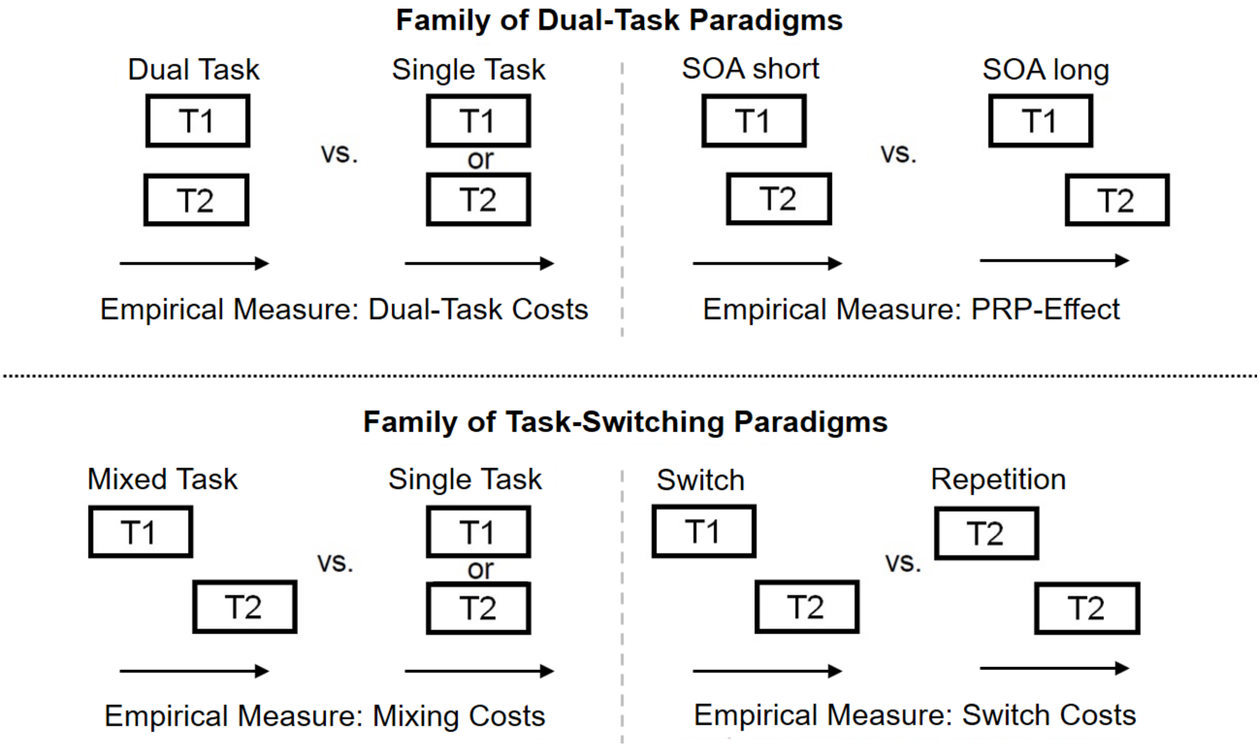

Figure 1. Graphical illustration of multitasking paradigms. T = task; SOA = Stimulus-Onset Asynchrony; PRP = Psychological Refractory Period.

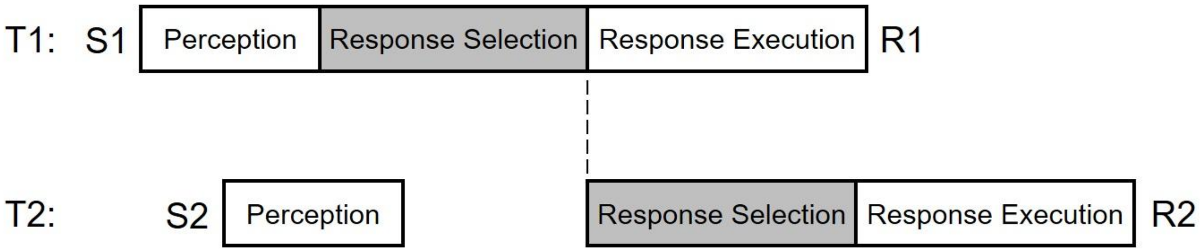

Figure 2. Schematic depiction of a serial central processing bottleneck at the stage of decision and response selection. T = task, S = stimulus, R = response. The shaded stage represents the central, capacity-limited stage.

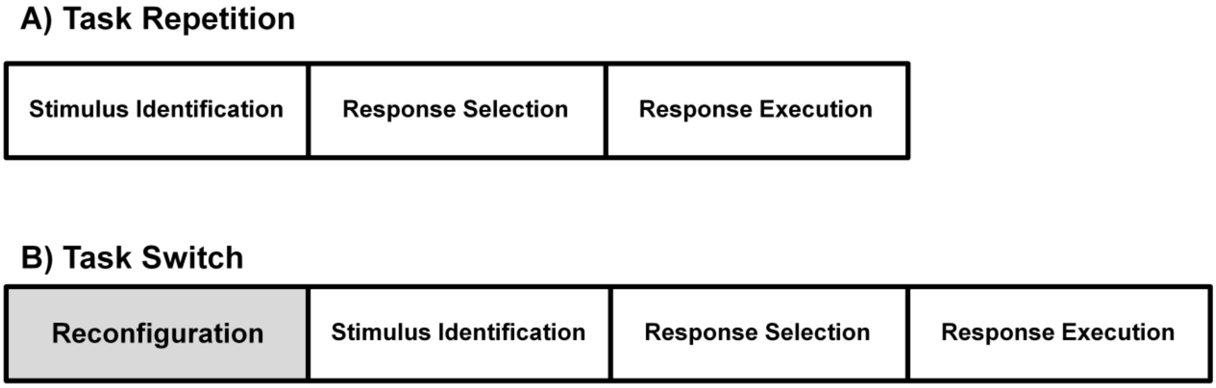

Figure 3. Structural account of switch costs in terms of the time taken by an additional processing stage of task-set reconfiguration. This is a simplified version that does not take into account that stimulus identification, response selection, and execution might also take longer in task switch than repetition trials.