Serial and Parallel Processing in Multitasking: Concepts and the Impact of Interindividual Differences on Task and Stage Levels

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Competing Interests: The authors have no competing interests to declare.

Raw data and stimulus material are available via the Open Science Framework at https://osf.io/tw8qx/?view_only=f5e4bec9428844e9b0434894b1d3a4c9

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This research was supported by a grant awarded to Jovita Brüning within the Priority Program 1772 on “Human performance under multiple cognitive task requirements: From basic mechanisms to optimized task scheduling” funded by the Deutsche Forschungsgemeinschaft (DFG) and by grant JA2307/6-1 funded by the DFG and awarded to Markus Janczyk. This study was not preregistered.

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Abstract

In multitasking research, a central question revolves around whether humans can process tasks in parallel. What 'in parallel' refers to, however, differs between research perspectives and experimental approaches. From a *task-level perspective*, parallel processing can be conceived as to whether complete tasks are processed in an overlapping manner and how this impacts task performance. In contrast, a large body of literature solely focuses on the central stage of response-selection and whether it can run in parallel with other processing stages, an approach we refer to as the *stage-level perspective*. Importantly, although each perspective addresses related topics and highlights inter-individual differences, they evolved through independent lines of research. In two experiments, we have taken a first step to investigate if individuals' tendencies for an overlapping versus serial processing mode on the task level are related to vulnerabilities for task interference on the stage level. Individual preferences for either task processing mode were assessed in the task switching with preview (TSWP) paradigm. Individuals' vulnerability for task interference was assessed with the backward crosstalk effect (BCE) in a classical dual-task. Our results suggest that individuals who prefer overlapping relative to serial task processing at the task level are less vulnerable to task interference during response selection, indicated by a smaller BCE. This difference, however, only emerged in the second experiment with an increased sample size and with task-stimuli that facilitate a bottom-up separation of tasks in the dual-task.

Keywords

multitasking; backward crosstalk; task switching; interindividual differences

Public Significance Statement

There is a considerable range from basic to more applied research in multitasking. However, few studies have tried to link the different research perspectives and experimental approaches employed in basic multitasking research, and even fewer have addressed their relation to more applied multitasking. The present study addresses this gap using an interindividual differences approach. We show that individuals who process multiple tasks in a parallel way in a less restrictive paradigm tend to be less vulnerable to task interference in a paradigm derived from basic multitasking research. Thereby, the study contributes to the literature by describing a relation between multitasking effects found on the level of specific processing stages and on the task level.

Serial and Parallel Processing in Multitasking: Concepts and the Impact of Inter-individual Differences on Task and Stage Levels.

Introduction

The idea that multitasking has detrimental effects on performance became a dominant claim in recent decades. Whether you chat with friends or browse the public media, the consensus is that multitasking doesn't actually work and is, thus, more harmful than useful (e.g., MacMillan, 2016; Rosen, 2008; Schindler, 2015). Arguments favoring this claim emerge from a still ongoing debate: Can we really process and perform tasks "in parallel", or is the introspective impression of parallel processing just the result of efficient task-scheduling, but essentially serial processing? At least, it is relatively clear that people often (if not always) engage in multitasking, that is, they perform two or more tasks with some temporal overlap.

An attempt to answer these questions must first consider what 'parallel processing' actually means. Although this seems rather simple at first glance, it turns out that the concept is used differently across research perspectives. One perspective on parallel processing relates to two-process theories of information processing. Examples are the distinction of automatic and controlled processes (Shiffrin & Schneider, 1977), volitional and automatic control of action (Norman & Shallice, 1986), reflective and impulsive systems (Strack & Deutsch, 2004), or fast and slow thinking (Kahneman, 2011). Common to these theories is the assumption that information processing either runs automatically, that is, via direct stimulus-response translations with no or only little voluntary control, or in a more controlled way, demanding deliberate allocation of attention (Norman & Shallice, 1986). In this context, it is often noted that only automatic processes can in principle run in parallel with other processes without necessarily affecting them, whereas controlled processing is essentially serial (Shiffrin & Schneider, 1977). This does not exclude the occurrence of interference effects between automatic and controlled processes, though. The latter can arise, for example, if automatic processing leads to an automatic attention capture (Shiffrin & Schneider, 1977), or to outcome conflicts with a controlled process running in parallel (Navon & Miller, 1987). A broader perspective on parallel processing, one that is also adopted here, is the one proposed by resource models of information processing (Kahneman, 1973; Navon & Gopher, 1979; Wickens, 1984, 2002). According to these models, the human information processing system has limited processing resources that can be shared by different cognitive processes. This implies that all sorts of cognitive processes can, in principle, run at the same time (i.e., 'in parallel'). However, this parallel processing may come along with interference effects due to the competition for resources in addition to possible interference related to the kinds of crosstalk effects mentioned above (see Schacherer & Hazeltine, 2021, for a recent discussion).

Another noteworthy distinction between research perspectives is how fine-grained (i.e., at which 'level') they address the issue of parallel processing: First, parallel processing can be considered on the level of specific information processing *stages,* and second, it can be considered on the level of *entire tasks*. The stage level is addressed by a large set of literature on basic mechanisms of multitasking in cognitive psychology (see, e.g., Koch et al., 2018; Pashler, 2000). Here, the question to what extent tasks are processed in parallel is addressed separately for the different processing stages from input to output with a main focus on the central stage of response selection. In contrast, human factors and human performance research often take a more holistic perspective on parallel processing on the task level. The main question addressed by this perspective is to what extent whole tasks can be performed concurrently by assessing concurrent task performance and comparing it to single-task performance (see, e.g., Navon & Gopher, 1979; Norman & Bobrow, 1976; Wickens et al., 1981, 2013). Whether options of parallel processing on the stage level are actually used to optimize concurrent performance on the task level is thus far unclear, though. In the following, we will point out similarities and differences between these two perspectives of parallel processing on the stage and the task level. We will also address the topic of inter-individual differences to assess whether there are hints to assume systematic inter-individual co-variations with respect to processing aspects on both levels. This would be necessary to allow investigating a relation between both by empirical means.

Serial and Parallel Processing at the Stage Level: Evidence from Dual-Task Research

When two speeded tasks are presented in short succession, response times (RTs) in Task 2 are prolonged the more the two tasks overlap temporally (i.e., the shorter the interval between the onset of the corresponding stimuli is; commonly termed the stimulus onset asynchrony, SOA). This effect is known as the psychological refractory period (PRP) effect (Telford, 1931) and has led to the development of the *central bottleneck model* (Pashler, 1994; Welford, 1952). According to this model, perceptual (encoding) processes and motor (execution) processes run ‘automatically’ (i.e., without capacity-limitation) and, thus, the corresponding stages can run in parallel to other processes of other tasks without affecting them. In contrast, for the central stage, commonly associated with response selection processes, a structural limitation is assumed which makes it impossible to select different responses in parallel and, therefore, enforces a strictly serial processing of the central stages on two tasks (see Janczyk & Kunde, 2020, for an elaboration of the central stage and the resulting problems).

During the last two decades, however, evidence has accumulated that contradicts the idea of strict seriality at central stages. One of these conflicting effects is the backward crosstalk (or correspondence) effect (BCE; Hommel, 1998; see also, e.g., Ellenbogen & Meiran, 2008, 2011; Janczyk, 2016; Janczyk, Renas, & Durst, 2018; Koob et al., 2020, 2021; Lien et al., 2007; Miller, 2006; Rieger & Miller, 2020; Thomson et al., 2010, 2015). In the seminal study by Hommel (1998, Exp. 1), participants were presented with colored letters, and asked to sequentially respond to the color with a manual left or right response (Task 1) and then to the letter identity with a vocal utterance of ‘left’ or ‘right’ (Task 2). Interestingly, RTs in Task 1 were longer when the vocal utterance of Task 2 was spatially incompatible to the corresponding manual response (e.g., a left keypress and the vocal utterance ‘right’). That is, a response compatibility effect in Task 1 was found, reflecting a backward effect of the second on the first response which contradicts the notion of strict seriality of response selection-related processes. Specifically, this observation suggests that, during Task 1 processing, Task 2 response information is already activated to some degree, which then interferes with Task 1 response selection (Janczyk, Renas, & Durst, 2018; Thomson et al., 2015; see also Miller, 2017; but see Hommel, 1998, and Lien & Proctor, 2002, for a slightly different interpretation). However, adopting ideas of resource models (Navon & Miller, 2002; Tombu & Jolicœur, 2003) offers another, perhaps more intuitive, interpretation of the BCE. Instead of sticking to the idea of strictly serial processing at the response selection stage and distinguishing this central stage from interfering response activation, these models conceptualize the entire response selection stage as a limited resource that can flexibly be shared between tasks. In other words, parallel (concurrent) response selection is possible for central stages, albeit less efficient as resources need to be split. The BCE can then be considered a result of concurrently running and, thereby, potentially interfering processes at central stages. More precisely, possible inter-individual differences in its size might result from two (not mutually exclusive) alternative sources. On the one hand, the size of the BCE might reflect how strongly participants central processing is affected by crosstalk. On the other hand, it might also reflect to what extent mental resources are simultaneously shared at the central stage (i.e., how much of parallel processing takes place at this stage).

The latter conceptualization would also imply a direct relationship between crosstalk and resource sharing. Some corroborating evidence for this assumption comes from the study by Lehle and Hübner (2009). These authors used a variant of a PRP experiment with the central and peripheral stimuli of a flanker task as stimuli for Task 1 and 2, respectively. Their results showed that the size of the crosstalk effect between both tasks was directly dependent on whether the participants were instructed to process both tasks in a parallel or in a serial way (see also Miller & Tang, 2020; Miller et al., 2009; and Fischer & Plessow, 2015, for a review). However, the particular experimental setup used in that study is hardly comparable to those typically used in BCE research

It is clear that parallel processing is a prerequisite for the BCE to occur and the BCE might become increased at the group level when implementing specific manipulations that enforce parallel processing. However, another explanation for the size of the BCE might be that it simply indicates how resilient participants are to interference effects. In particular, it might be too strict to assume that parallel processing always implies the occurrence of crosstalk (see also, the 'interference criterion' in Neumann, 1984, for a similar reasoning) for all participants. Hence, within a group of participants, variations in the size of the BCE might simply reflect inter-individual differences in the ability to cope with task interference. In fact, there is at least some anecdotal evidence for this assumption. Remarkably, already Hommel (1998) reported that about 30-40% of his participants did not show the typical BCE but rather a reversed or very small BCE (see, e.g., Experiment 4, p. 1378). He proposed that those individuals were able to actively inhibit the automatic response activation in Task 2 while still performing Task 1. Alternatively, one could assume that individuals showing little or no BCEs were just able to better maintain concurrently running (central) processes of each task without large crosstalk effects, for example, due to a larger amount of available resources or more efficient protection against interference of concurrently activated response sets. In BCE research, such inter-individual differences have received no or only little attention subsequently, but re-analyses of published data from our laboratories (i.e., Durst & Janczyk, 2019; Janczyk et al., 2017; Janczyk, Mittelstädt, & Wienrich, 2018; Koob et al., 2020) confirm the observation by Hommel (1998). Most interesting in the context of the present research is that possibly related inter-individual differences can also be observed for processing at the level of entire tasks, there reflected in an individual preference for a more serial or parallel mode of processing, as will be outlined in the next section.

Serial and Parallel Processing at the Task Level: Evidence From Task Switching With Preview

From the task-level perspective, the performance and efficiency of whole tasks (instead of a single stage) is of interest. By considering general task performance, ‘parallel processing’ is conceptualized more broadly: The focus is not any longer on the central or peripheral processing stages, but on how the possibilities and constraints provided by options for parallel processing on different stages of processing are actually used to optimize the performance in multitasking at the level of entire tasks.

This was the main perspective taken by classical multitasking research in the 1960ies to 80ies. These studies usually involved the concurrent performance of two independent threads of discrete tasks or combinations of a discrete and a continuous task (e.g., tracking). The focus was on the determinants of multitasking efficiency, operationally defined, for example, by means of performance-operating characteristics (Norman & Bobrow, 1976) and theoretically driven by resource models of human information processing (Kahneman, 1973; Navon & Gopher, 1979; Norman & Bobrow, 1975). This research suggested that the possibilities to make use of parallel processing in concurrent task performance directly depend on the similarity of task demands. This has led to the development of the multiple-resource theory (Wickens, 1980, 1984), which seems particularly useful to derive predictions about the efficiency of multitasking performance (Wickens, 2002). Moreover, evidence was reported that individuals differ in their preference for using a more serial compared to parallel processing mode when performing two tasks concurrently. This claim was derived from studies specifically analyzing the scheduling of responses to different tasks in what might be referred to as ‘free concurrent dual-tasking’, that is, the concurrent performance of two independent threads of tasks (see, e.g., Damos & Wickens, 1980; Damos et al., 1983).

More systematic evidence has recently been provided by task switching research, using a new experimental approach referred to as *task switching with preview* (TSWP;

Brüning & Manzey, 2018; Reissland & Manzey, 2016). This research allows to identify an individual's preference for a serial or parallel mode of processing on the task level while keeping essential characteristics of classical task switching experiments. Its procedure derives from the alternating runs approach of Rogers and Monsell (1995) in that it uses an AAABBB task scheme, but with the extension of a preview of the next task switch stimulus. Thus, while working on the three trials of Task A (B), participants always are provided with a preview of the stimulus of the upcoming Task B (A). Whereas the tasks in TSWP still need to be responded to sequentially, the concurrent preview of the next stimulus of the task to be switched to allows for at least some, but does not enforce, parallel processing, which can be used to reduce switch costs or even produce switch benefits. Importantly, however, participants have no immediate deadline for responding to the upcoming task and are not specifically instructed to pre-process it. Thus, any use of the preview stimulus for some (parallel) overlapping processing can be considered indicative of individual preferences concerning the use of a more parallel compared to serial mode of processing. For example, in the study by Reissland and Manzey (2016), half of the sample used the stimulus preview to prepare and thus speed up their response in the upcoming task switch. Hence, these participants used options of parallel processing at the stage level to optimize their performance. However, the other half did not so and produced switch costs like those known from task switching experiments without preview. Presumably, these individuals even avoided parallel encoding of the preview stimulus at the perceptual stage to keep the two tasks as separate as possible, maybe to avoid any risks of task interference which might result from overlapping processing. Subsequent studies replicated this observation with a somewhat more sophisticated classification of participants into three groups, referred to as *serials*, *semi-overlappers*, and *overlappers* based on how often they exhibited evidence of using the preview (i.e., overlapping processing) at task switches. Remarkably, these studies also demonstrated significant performance benefits in terms of higher task throughput due to overlapping processing (Brüning & Manzey, 2018; Brüning et al., 2020, 2021).

The Present Study

Given the observations of inter-individual differences in the resilience to interference on the level of processing stages and individual preferences for a serial versus parallel mode of processing entire tasks, it is straightforward to ask: To what extent are these differences related to each other? An intuitive suggestion would be that individuals who avoid engaging in any sort of overlapping processing on the level of entire tasks (i.e., those preferring serial processing) do so, because they would suffer from interference effects in case of parallel processing on the central processing stage. This would be indicated by a large BCE then. For individuals who use options of overlapping processing on a task level, it can be expected that they show some resilience towards interference effects of parallel processing on the level of processing stages, reflected in a smaller (or even no) BCE. In either case, a descriptive pattern of overlappers depicting a smaller BCE than serials would emerge. With the present study, we aim to demonstrate an empirical relation between processing modes in the TSWP and the size of the BCE. For this purpose, we conducted two experiments by combining inter-individual differences research focusing on processing on the task level and stage level using the TSWP paradigm and a dual-task, respectively.

It should be noted that each experimental paradigm evolved in its own research area and comes with its own setup that has proven well to create the intended effect. In order to elaborate on the link between the inter-individual differences observed with both approaches, an important pre-condition is to reliably induce the respective effects. Thus, we applied the two experimental paradigms with the specific experimental setups and the corresponding analyses in a way that has proven successful in the past.

Experiment 1

The purpose of Experiment 1 was to examine whether overlapping versus serial processing at the task level as measured with the TSWP paradigm is mirrored by systematic inter-individual differences at the stage level, indicated by the size of the BCE in a dual-task. More precisely, we classified participants as *overlappers*, *semi-overlappers*, and *serials* based on a typical TSWP paradigm and then tested whether (semi-)overlappers and serials differ in the size of their BCEs in a typical dual-task.

Method

Transparency and Openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study, and we follow JARS (Kazak, 2018). All data, analysis code, and stimuli material are available at https://osf.io/tw8qx/?view_only=f5e4bec9428844e9b0434894b1d3a4c9. Data were analyzed using R, version 4.0.3 (R Core Team, 2020) and the packages dplyr (Wickham et al., 2021; v. 1.0.3), tidyr (Wickham, 2020; v. 1.1.2), ggplot2 (Wickham, 2016; v. 3.3.3), Rmisc (Hope, 2013; v. 1.5), summarytools (Comtois, 2020; v. 0.9.8), ez (Lawrence, 2016; v. 4.4-0), schoRsch (Pfister & Janczyk, 2016; v. 1.9.1), BayesFactor (Morey & Rouder, 2018; v. 0.9.12-4.2), plotrix (Lemon, 2006; v. 3.8-1), and nlme (Pinheiro et al., 2021). This study's design and its analysis were not pre-registered.

Participants

Forty-eight people participated in this study, twenty-four in the Berlin lab and the Tübingen lab each (34 female, mean age = 24.7 years, range = 19-35 years, 46 right-handed, two left-handed). Power analysis was conducted using G*Power 3.1 (Faul et al., 2009) for our effect of interest, that is, the interaction between response compatibility (repeated measure) and TSWP group (between-participants factor). Since there is yet no empirical data regarding a comparison of BCEs regarding TSWP groups on which we could base our estimation of a reasonable effect size, we assumed effects of $\eta_p^2 \geq .06$ to be of relevance (i.e., a 'medium' effect size according to Cohen, 1988; although which effect sizes are of relevance may vary across research contexts, Fritz et al., 2012). Assuming a power of $1 - \beta = .80$ and $\alpha = .05$, the overall sample size required to detect such an effect was *n* = 42. Note that this sample size is within the range of previous studies using the TSWP to assess individual preferences (Brüning & Manzey, 2018; Brüning et al., 2021). Data from five participants were discarded due to a large number of errors (> 20%) within the dual-task. Additionally, for one participant, one task switching block and two single-task blocks (one for each task) during TSWP were lost because of computer malfunction. Since this participant still produced a reasonable number of trials in the TSWP paradigm, the data were kept within the sample. Participants were naïve regarding the hypotheses of this experiment, reported normal or corrected-to-normal vision, and signed informed consent before data collection. To ensure motivation, participants received a monetary bonus for each correct answer within the TSWP, which could add up to €5.

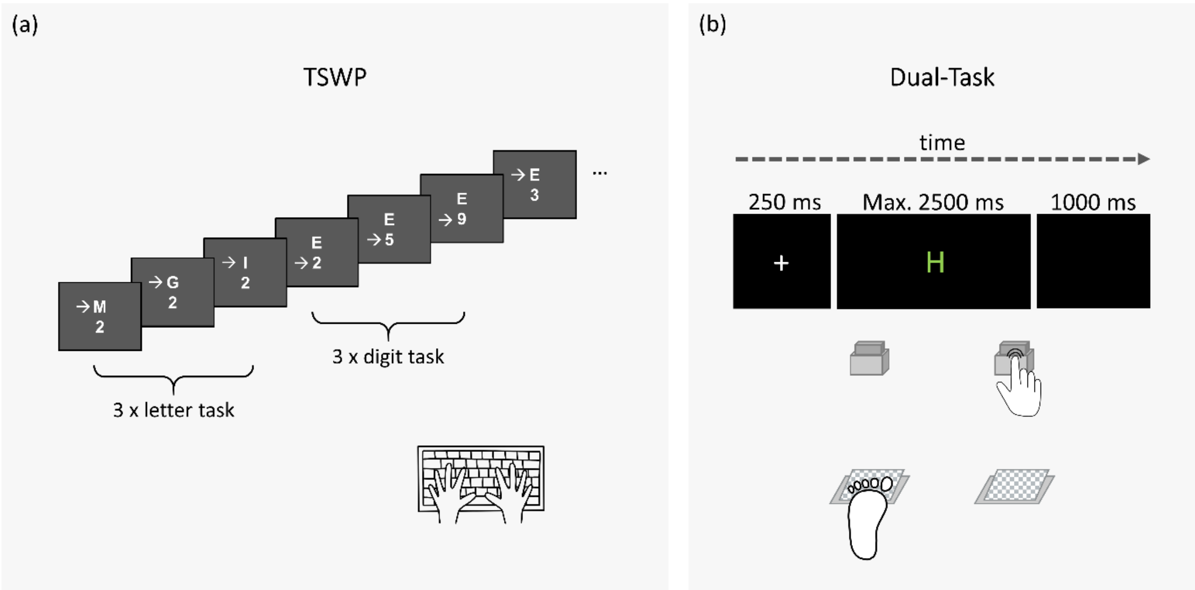
Stimuli, Apparatus, and Tasks

Stimulus presentation and response collection were controlled by a standard PC. A general outline of the experimental setup is depicted in Figure 1. Within the *TSWP paradigm*, participants performed a, for the task switching literature typical, digit and a letter classification task (e.g., Rogers & Monsell, 1995). In the digit task, a single digit called for classification according to its parity (2, 4, 6, 8 vs. 3, 5, 7, 9). In the letter task, participants had to categorize a single capital letter as a vowel or consonant (A, E, I, U vs. G, K, M, R). Stimuli were displayed in white against a dark gray background. Within single-task blocks, only one stimulus was presented in the center of the screen. In task switching blocks, stimuli for both tasks were presented simultaneously and within close spatial proximity to each other, one closely above and one closely below the center of the screen. A white arrow pointing at either the digit or the letter indicated the current task (see Figure 1a). Responses were collected using a standard USB-keyboard with each hand assigned to one task. The keys ‘K’ and ‘L’ were used with the index and middle finger of the right hand, respectively. The keys ‘S’ and ‘A’ were used with the index and middle finger of the left hand, respectively. Task-hand assignment was counterbalanced across participants. Additionally, relevant keys were marked by colored points for easier recognition.

Stimuli for the *dual-task* were the letters ‘S’ or ‘H’, presented in red or green color, as it is common in BCE research (e.g., Hommel, 1998). Letter identity served as the Task 1 stimulus (S1) and the color served as the Task 2 stimulus (S2). Stimuli were presented centrally against a black background. Participants responded to S1 with a left or right index finger keypress (R1), using response keys placed on the left- and right-hand side of the table. S2 was answered with a left or right pedal press (R2), using foot pedals placed on the floor (as used earlier in, e.g., Durst & Janczyk, 2019; Janczyk, 2016; see Figure 1b). Stimulus-response mappings were counterbalanced across participants.

Figure 1

Trial Structure and Tasks of the Experimental Procedure



Note. (a) During task switching blocks within TSWP, participants worked on a digit and a letter classification task, following an AAABBB pattern. A white arrow pointed at the corresponding letter or digit location to indicate which task was currently relevant. Each task was associated with a separate hand and responses were given with the corresponding index- or middle-finger. (b) Within the dual-task, each trial started with a white fixation cross, followed by a colored letter. Participants responded to the letter identity with a manual left/right key press using their index-fingers, and subsequently to the letter color with a left/right pedal press. In this example, the letter 'H' called for a right-hand response, while the color 'green' called for a left-foot response. Thus, this trial would be R1-R2 incompatible.

Procedure

All participants performed both TSWP and the dual-task within a single session of about 60 minutes in a counterbalanced order. A session started with general instructions and signing consent. After that, the first paradigm was administered. Once upon finishing this part, participants contacted the experimenter, who started the second paradigm. Instructions were presented in written form on the computer screen, were read self-paced, and emphasized speed while maintaining errors at a low rate.

During the *TSWP* part, participants first performed each task in isolation (each 45 sec), followed by one task switching block for task-familiarization (60 sec). They then completed four experimental runs. Each run comprised a 120 seconds task switching block with one subsequent 60 seconds block of each single-task, with the order of single-tasks counterbalanced across runs. Single-task blocks were included to control for practice effects, because the identification of "fast switches" as the critical variable to identify overlapping processing requires a stable reference in terms of single-task response speed (see design and analyses, for further information). Within each task switching block, tasks were presented in a predictable AAABBB pattern, resembling an alternating runs scheme (Rogers & Monsell, 1995). With three repetitions for each task, trials in task switching blocks can thus be distinguished into switch (A**B**BBA), pure-repetition (AB**B**BA), and pre-switch (ABB**B**A) trials. Stimuli remained on the screen until a response for the respective task was registered. Then, the stimulus was immediately replaced by another randomly-drawn stimulus of the corresponding task. Note that the response-stimulus interval was zero and stimulus-repetitions were not possible. Importantly, digits and letters were visible all the time, and responding in one task did not change the stimulus in the other task (see Figure 1). After each block, participants received feedback about the number of their responses as well as the number and percentage of correct responses.

In the *dual-task*, each trial started with a white fixation cross (250 ms) which was immediately replaced with a red or green colored 'S' or 'H'. The colored letter remained on the screen until both responses were given or 2500 ms elapsed. In case of an error in the current trial, respective feedback was provided on the screen (1000 ms), and the next trial started after an inter-trial interval of 1000 ms. Twenty randomly drawn trials were administered for task-familiarization first. Afterwards, participants worked on ten experimental blocks of 40 trials each, resulting from ten repetitions of the four possible S1 ('S' or 'H') and S2 (green or red) combinations presented in a random order within each block. A trial was considered R1-R2 compatible when the required (correct) responses to both

Task 1 and 2 were to-be-given on the same side. Otherwise, the trial was considered R1-R2 incompatible.

Design and Analyses

Data were analyzed mirroring previous studies (TSWP: e.g., Brüning, Reissland, & Manzey, 2020; BCE: e.g., Koob et al., 2020). Because trials of the *TSWP paradigm* had no time limit, RTs longer than 4000 ms were excluded first (0.025%). For the analysis of RTs, only correct trials were considered. Subsequently, trials with RTs deviating more than 2.5 standard deviations (SDs) from the participants' mean correct RT in the according trial type and experimental block were excluded (3.31% and 3.44% for the digit and letter task, respectively). To capture an individual's tendency to pre-process an upcoming task in terms of overlapping processing, we determined for each participant the proportion of switches that represented so called *fast switches* (see also, Brüning & Manzey, 2018, p. 98; Brüning et al., 2021, p. 583). Fast switches are defined as correct switch trials that fulfill two conditions. First, the corresponding RT is at least as fast as the 25% fastest single-task RTs in the upcoming single-task block. Remember that single-task blocks repeat after each task switching block, and thus the comparison between switch RTs and single-task RTs remains comparable across all experimental runs (i.e., remains stable irrespective of potential practice effects). Second, fast switches are not the result of a compensational prolongation in the three trials before the switch. To quantify this, we first calculated intervals that encompass all three responses before a switch and then averaged the respective intervals for all non-fast switch trials (i.e., for switches that are slower than 25% of the fastest single-task RTs in the upcoming single-task block). The key idea is that, on average, responses that precede a fast switch may contain additional time used to process the preview (i.e., in terms of a compensational prolongation), whereas responses that precede non-fast switches should not. By contrasting the interval that precedes a fast switch with the averaged interval preceding all non-fast switches, we can quantify a potential compensational prolongation. If the compensation outweighs the performance benefit on a switch trial (i.e., is larger than the difference between switch RT and the average single-task RT), the respective switch is no longer considered a fast switch. We then proceeded to calculate the fast switch rate, defined as the proportion of correct fast switches relative to all correct switch trials. If a participant is a *(semi-)overlapping processor*, its fast switch rate is expected to be relatively high. If a participant is a *serial processor*, its fast switch rate is expected to be relatively low. To determine which fast switch rates can be considered “high” or “low”, we took the distribution of fast switch rates under a task switch condition without preview provided within the data set by Brüning and Manzey (2018). More detailed information on the derived cut-off values for the classification can be found in the Appendix (see also Brüning & Manzey, 2018; Brüning et al., 2021).

Mean correct RTs and percentage errors (PEs) of the TSWP single-task conditions were submitted to submitted to separate analyses of variance (ANOVAs) with task (digit vs. letter task) as a repeated measure and group (overlappers vs. semi-overlappers vs. serials) as a between-participants variable. Data from the TSWP task switching condition were submitted to ANOVAs with trial type (pure-repetition vs. pre-switch vs. switch) as a repeated measure and group (overlappers vs. semi-overlappers vs. serials) as a between-participants variable.[1] Note that the ANOVA on RTs during task switching conditions primarily served as a check to ensure that (semi-)overlappers indeed have shorter switch RTs without signs of a compensational prolongation.

For the dual-task, practice trials, trials with unspecific errors (no response, wrong response order etc.), and trials with an inter-response interval (IRI) of less than 50 ms were excluded first.[2] For the analysis of RTs, only entirely correct trials were considered, and RTs

[1] In a preliminary analysis, *task* (i.e., letter vs digit task) had only a main effect on RTs, but did not result in any interactions. We thus averaged across the digit and the letter task for these analyses.
[2] Excluding trials with short IRIs was done to reduce the impact of response grouping. Rerunning the analyses with higher IRI cut-off values of 100 ms or 150 ms left the result pattern unchanged.

were excluded if these deviated more than 2.5 SDs from the individual cell mean (2.87% and 2.76% of the trials were considered as outliers for Task 1 and 2, respectively).

Because the size of the BCE increases with longer RTs (e.g., Ellenbogen & Meiran, 2008, 2011; Hommel, 1998), we performed a distributional analysis of the BCE data. For correct Task 1 and 2 RTs, we calculated 10 evenly spaced percentiles (5%, 15%, …, 85%, 95%), separately for each participant and R1-R2 compatibility condition (i.e., R1-R2 compatible vs. incompatible). The results were then entered into an ANOVA with compatibility (R1-R2 compatible vs. incompatible) and percentile (5%, 15%, …, 85%, 95%) as repeated measures and TSWP group (overlappers vs. semi-overlappers vs. serials) as a between-participants variable. Furthermore, for reasons that will become clear in the results section, we also performed an identical ANOVA on the log-transformed RTs. For the analyses of Task 1 and 2 errors, mean PEs were submitted to an ANOVA with R1-R2 compatibility as repeated measures and TSWP group as a between-participants variable. In case the sphericity assumption was violated, *p*-values were corrected according to the procedure by Greenhouse and Geisser (1959), and the corresponding ε is reported. Finally, while we believe that using the classification approach in the TSWP facilitates the understanding of the BCE analyses, it inherently reduces information (MacCallum et al., 2002). To address this issue, we additionally performed a continuous analysis by calculating a regression with individual fast switch rates as the predictor and BCE values as the criterion. In particular, we performed a generalized least-squares regression with an exponential variance function (Gałecki & Burzykowski, 2013).[3]

Results

Based on the distribution of fast switch rates in the TSWP, fourteen participants were classified as overlappers, 10 as semi-overlappers, and 19 as serials.

[3] Performing a normal least-squares regression yielded the same conclusions.

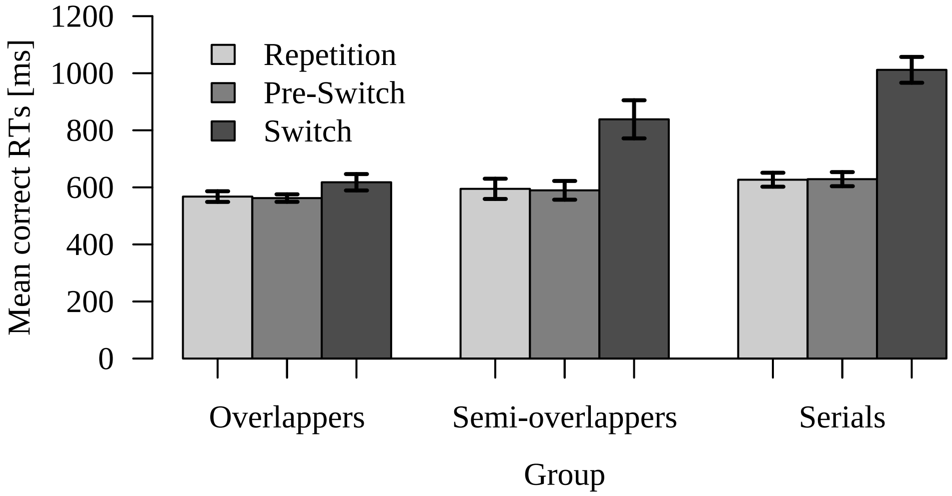
TSWP

Mean correct single-task RTs were 600 ms and 571 ms for overlappers, 652 ms and 620 ms for semi-overlappers, and 686 ms and 638 ms for serials (digit and letter task, respectively). Accordingly, the main effect of group was significant, $F(2, 40) = 9.66$, $p < .001$, $\eta_p^2 = .33$, as was the main effect of task, $F(1, 40) = 51.16$, $p < .001$, $\eta_p^2 = .56$. The interaction was not significant, $F(2, 40) = 1.77$, $p = .184$, $\eta_p^2 = .08$. Less errors were made in the letter task (3.08%, 3.87%, 3.05% for overlappers, semi-overlappers, and serials, respectively) compared with the digit task (3.87%, 4.73%, 4.72%, respectively), $F(1, 40) = 20.55$, $p < .001$, $\eta_p^2 = .34$. Neither the main effect of group, $F(2, 40) = 0.29$, $p = .753$, $\eta_p^2 = .01$, nor the interaction between group and task were significant, $F(2, 40) = 1.61$, $p = .213$, $\eta_p^2 = .07$.

Mean correct RTs in task switching conditions are visualized in Figure 2. Overall, mean RTs increased from overlappers to semi-overlappers and serials, with serials having the longest overall RTs, $F(2, 40) = 21.09$, $p < .001$, $\eta_p^2 = .51$. Regarding the main effect of trial type, overall RTs were longest for switch trials while RTs were similar for repetitions and pre-switches, $F(2, 80) = 196.09$, $p < .001$, $\eta_p^2 = .83$, $\varepsilon = .550$. As expected from the classification though, this effect was almost absent for overlappers, but clearly present for semi-overlappers and serials, reflected by a significant interaction, $F(4, 80) = 41.66$, $p < .001$, $\eta_p^2 = .68$, $\varepsilon = .550$. Mean PEs were 2.59%, 2.65%, and 3.50% for overlappers, 2.55%, 3.02%, and 3.20% for semi-overlappers, and 3.47%, 4.67%, and 3.50% for serials (repetition, pre-switch, and switch trials, respectively). None of the main effects nor the interaction reached statistical significance; group, $F(2, 40) = 0.89$, $p = .420$, $\eta_p^2 = .04$; trial type, $F(2, 80) = 1.95$, $p = .149$, $\eta_p^2 = .05$; trial type × group, $F(4, 80) = 2.07$, $p = .093$, $\eta_p^2 = .09$.

Figure 2

Mean Correct RTs of the TSWP Paradigm as a Function of Trial Type in Task Switching Conditions and TSWP Group (Experiment 1)



Note. Error bars are 95% confidence intervals after removing inter-subject variability (Morey, 2008), calculated separately for each group.

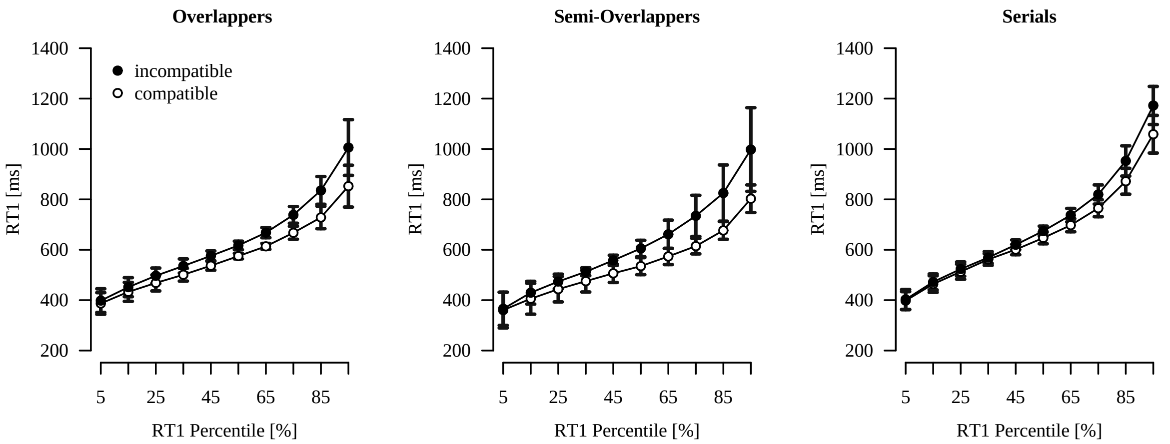
Dual-Task

Mean correct Task 1 RT percentiles are visualized in Figure 3. Unsurprisingly, responses were slower with higher percentiles, *F*(9, 360) = 292.06, $p < .001$, $\eta_p^2 = .88$, ε = .126. Responses were overall faster in R1-R2 compatible (604 ms) relative to incompatible trials (656 ms), *F*(1, 40) = 25.73, $p < .001$, $\eta_p^2 = .39$, thus a BCE was present. This BCE became larger with slower responses, reflected by a significant interaction of R1-R2 compatibility and percentile, *F*(9, 360) = 21.11, $p < .001$, $\eta_p^2 = .35$, ε = .169. When looking closer at the overall RT distributions between groups, it becomes apparent that serials produced a higher amount of slow responses relative to (semi-)overlappers, indicated by a significant interaction between group and percentile, *F*(18, 360) = 3.37, $p = .038$, $\eta_p^2 = .14$, ε = .126. The related main effect of group, however, was not statistically significant, *F*(2, 40) = 2.00, $p = .149$, $\eta_p^2 = .09$. Important for the present study, neither the two-way interaction between group and R1-R2 compatibility, *F*(2, 40) = 1.09, $p = .345$, $\eta_p^2 = .05$, nor the three-way interaction between group, R1-R2 compatibility, and percentile reached statistical significance, $F(18, 360) = 0.57$, $p = .640$, $\eta_p^2 = .03$, $\varepsilon = .169$. The BCE was thus not reliably different between groups (descriptive BCE values: 56 ms, 77 ms, and 37 ms for overlappers, semi-overlappers, and serials, respectively). Having obtained a null-effect with frequentist inferential statistics, we also calculated Bayes factors for the two-way interaction between group and R1-R2 compatibility and the three-way interaction between group, R1-R2 compatibility, and percentile, using the default priors within the R package BayesFactor (Morey & Rouder, 2018; v. 0.9.12-4.2). Omitting each interaction from the full ANOVA model led to anecdotal evidence for the alternative for the two-way interaction, $BF_{01} = 0.78$, and strong evidence for the null for the three-way interaction, $BF_{01} = 744.11$.

Because serials (surprisingly) depicted slower responses compared to (semi-)overlappers, we re-ran our analysis on Task 1 RTs with log-transformed RTs. The reason is that the size of the BCE increases with longer RTs, which might have led to an overestimation of an otherwise smaller BCE in the group of serials, thereby neutralizing possible differences. Thus, by analyzing log-transformed RTs, we aimed to provide more control for the different RT levels across groups – a method also common in aging research to control for age-related RT differences (e.g., see Giesen et al., 2015; Janczyk, Mittelstädt, & Wienrich, 2018; Pritchard & Neumann, 2009; Puccioni & Vallesi, 2012; but see Faust et al., 1999, for critical comments). Yet, the transformation did not change the conclusions from the previous ANOVA: percentile, $F(9, 360) = 978.69$, $p < .001$, $\eta_p^2 = .96$, $\varepsilon = .158$; R1-R2 compatibility, $F(1, 40) = 25.81$, p < .001, $\eta_p^2 = .39$; group, $F(2, 40) = 2.20$, $p = .124$, $\eta_p^2 = .10$; R1-R2 compatibility × percentile, $F(9, 360) = 17.39$, $p < .001$, $\eta_p^2 = .30$, $\varepsilon = .224$; group × percentile, $F(18, 360) = 4.23$, $p = .010$, $\eta_p^2 = .17$, $\varepsilon = .158$; group × R1-R2 compatibility; $F(2, 40) = 1.08$, $p = .348$, $\eta_p^2 = .05$; group × R1-R2 compatibility × percentile, $F(18, 360) = 0.56$, $p = .694$, $\eta_p^2 = .03$, $\varepsilon = .224$.

Figure 3

Mean Correct Task 1 RTs of the Dual-Task as a Function of R1-R2 Compatibility, TSWP Group, and RT Percentile (Experiment 1)



Note. Error bars are 95% confidence intervals after removing inter-subject variability (Morey, 2008), calculated separately for each group.

Mean PEs in Task 1 are summarized in Table 1. More errors were made in R1-R2 incompatible compared with compatible trials, $F(1, 40) = 30.22$, $p < .001$, $\eta_p^2 = .43$. Descriptively, serials committed more errors as semi-overlappers or overlappers, but the corresponding main effect did not reach statistical significance, $F(2, 40) = 1.65$, $p = .204$, $\eta_p^2 = .08$. The interaction between group and R1-R2 compatibility was also not significant, $F(2, 40) = 0.25$, $p = .783$, $\eta_p^2 = .01$.

Table 1

Mean PEs of Tasks 1 and 2 of the Dual-Task as a Function of R1-R2 Compatibility and TSWP Group in Experiment 1

	Task 1			Task 2		
	Compatibility			Compatibility		
TSWP Group	Incompatible	Compatible	Δ	Incompatible	Compatible	Δ
Overlappers	3.3	0.9	2.4	5.9	2.9	3.0
Semi-Overlappers	2.8	0.9	1.9	6.4	3.8	2.6
Serials	4.3	1.7	2.6	6.0	5.2	0.8

Note. Δ = difference between R1-R2 compatible and incompatible trials, that is, the crosstalk effect within the respective TSWP group.

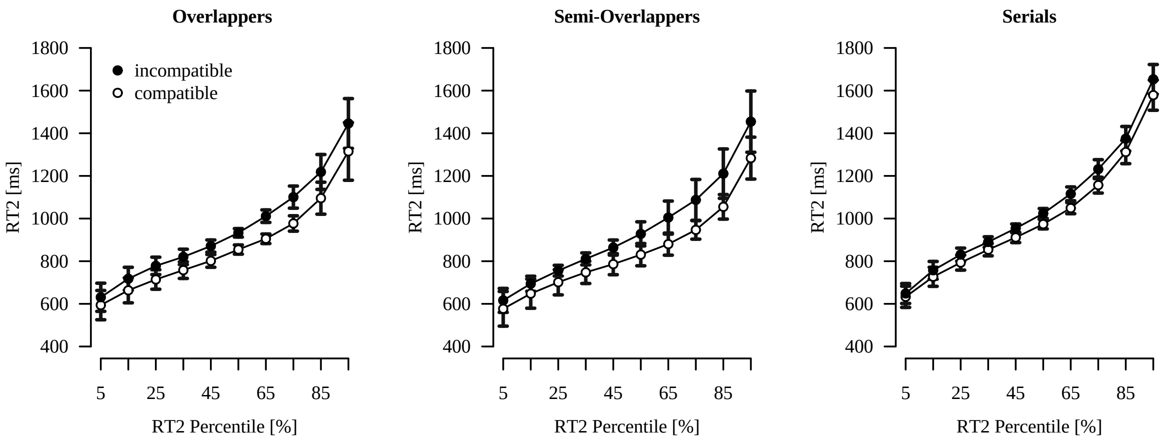
Mean correct Task 2 RT percentiles are visualized in Figure 4. Responses were slower with higher percentiles, $F(9, 360) = 374.92$, $p < .001$, $\eta_p^2 = .90$, $\varepsilon = .130$, and overall faster in R1-R2 compatible (921 ms) relative to incompatible (992 ms) trials, $F(1, 40) = 34.07$, $p < .001$, $\eta_p^2 = .46$. This difference became larger with slower responses, $F(9, 360) = 12.47$, $p < .001$, $\eta_p^2 = .24$, $\varepsilon = .206$. Serials generally responded slower and displayed a wider RT distribution compared to overlappers or semi-overlappers, reflected by a significant main effect of group, $F(2, 40) = 3.65$, $p = .035$, $\eta_p^2 = .15$, and a significant interaction between group and percentile, $F(18, 360) = 3.17$, $p = .044$, $\eta_p^2 = .14$, $\varepsilon = .130$. Neither the two-way interaction between group and R1-R2 compatibility, $F(2, 40) = 1.32$, $p = .277$, $\eta_p^2 = .06$, nor the three-way interaction between group, R1-R2 compatibility, and percentile did reach statistical significance, $F(18, 360) = 0.84$, $p = .496$, $\eta_p^2 = .04$, $\varepsilon = .206$. Descriptively, the compatibility effects for overlappers, semi-overlappers, and serials were 85 ms, 97 ms, and 49 ms, respectively.

Similar to the analysis of Task 1, we conducted an analogues ANOVA on the log-transformed RTs of Task 2. The conclusions remained unchanged: percentile, $F(9, 360) =$

781.45, $p < .001$, $\eta_p^2 = .95$, $\varepsilon = .151$; R1-R2 compatibility, $F(1, 40) = 35.76$, $p < .001$, $\eta_p^2 = .47$; group, $F(2, 40) = 3.78$, $p = .031$, $\eta_p^2 = .10$; R1-R2 compatibility × percentile, $F(9, 360) = 4.90$, $p = .008$, $\eta_p^2 = .11$, $\varepsilon = .238$; group × percentile, $F(18, 360) = 2.30$, $p = .094$, $\eta_p^2 = .10$, $\varepsilon = .151$; group × R1-R2 compatibility, $F(2, 40) = 1.65$, $p = .205$, $\eta_p^2 = .08$; group × R1-R2 compatibility × percentile, $F(18, 360) = 0.53$, $p = .728$, $\eta_p^2 = .03$, $\varepsilon = .238$.

Figure 4

Mean Correct Task 2 RTs of the Dual-Task as a Function of R1-R2 compatibility, TSWP Group, and RT Percentile (Experiment 1)



Note. Error bars are 95% confidence intervals after removing inter-subject variability (Morey, 2008), calculated separately for each TSWP group.

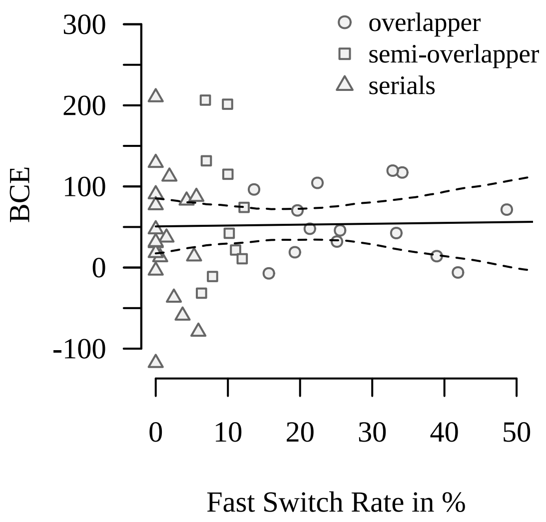
Mean PEs in Task 2 are summarized in Table 1. More errors were committed in R1-R2 incompatible compared with compatible trials, $F(1, 40) = 13.62$, $p = .001$, $\eta_p^2 = .25$. No other effect was statistically significant: group, $F(2, 40) = 0.62$, $p = .546$, $\eta_p^2 = .03$; group × R1-R2 compatibility, $F(2, 40) = 1.64$, $p = .207$, $\eta_p^2 = .08$.

Regression Analysis

In a final exploratory analysis, we performed a generalized-least squares regression with the fast switch rate as the predictor and the individual BCE values as the criterion. Because we noticed that the variance of the BCE values decreased with higher fast switch rates, we allowed the residuals of the regression to decrease exponentially. A scatter plot of the raw data and the estimated regression line is presented in Figure 5. As is evident, there was hardly any relationship and the corresponding slope turned out to be non-significant, $t(41) = 0.18$, $p = .861$, $\beta = 0.11$. Interestingly, we were able to replicate Hommel's (1998) observation that a subset of participants (here 21%) exhibited a negative BCE.

Figure 5

Individual Mean BCE Values Within the Dual-Task as a Function of the Respective Fast Switch Rates in the TSWP paradigm (Experiment 1)



Note. The solid black line is the fitted regression line. The curved and dashed lines depict the upper and lower boundary of a 95% bootstrapped confidence interval.

Discussion

The purpose of Experiment 1 was to examine a possible relation of a serial versus overlapping processing mode at the task level and the vulnerability for task interference at the stage level. To assess parallel processing at the task level, participants were tested in the TSWP paradigm. To assess the vulnerability for task interference related to parallel processing at the stage level, participants were tested in a dual-task and the BCE was measured.

Based on the TSWP paradigm, overlappers were identified as those individuals, who processed the preview stimulus (of the other task) at least partly while still performing the currently requested task. This was reflected in reduced switch costs without compensatory prolonged responses on repetitions or pre-switch trials. Serials, on the other hand, strived to shield tasks from each other, leading to a pronounced time cost on switch trials similar as in task switching experiments without a preview. However, the assumption that overlappers and serials would differentially suffer from interference effects in case of parallel processing on the central processing stage did not receive support. Instead, serials produced a descriptively smaller BCE than (semi-)overlappers. When calculating a regression on the individual fast switch rates, no relationship between fast switch rates and the BCE was revealed, descriptively reflected by the almost horizontal regression line in Figure 5. In terms of inferential statistics, the overall BCE was not significantly different between the TSWP groups, and a complementary analysis using Bayes factors led to inconclusive results, that is, neither in favor nor against the null. Further, there was no significant evidence for a different temporal course of the BCE across RTs, and the corresponding Bayes factor strongly favored the null.

There are, however, reasons for caution that prevent us from drawing strong conclusions. First, we might not have found the expected relationship between the modes of processing in the TSWP and the size of the BCE because the dual-task employed an integral stimulus (i.e., a colored letter), in which the relevant stimulus features for both tasks are necessarily processed simultaneously. As such, the risk of crosstalk between the two tasks might have been particularly high (see Ellenbogen & Meiran, 2011). Consequently, even participants who showed a preference for overlapping processing in TSWP might have been unable to process both tasks in parallel without considerable crosstalk effects. That is, the presentation of an integral stimulus and the related enforced simultaneous processing of both tasks might have caused interference effects to such a degree that it masked more subtle differences between the different TSWP groups with respect to resilience to interference in overlapping processing. This would also fit to the observation in a previous TSWP study where preferences for overlapping versus serial processing were assessed based on tasks involving different degrees of crosstalk risk operationalized by using univalent versus bivalent task stimuli (Brüning & Manzey, 2018). In this study, participants identified as (semi-)overlappers in the condition with univalent task stimuli adopted a more serial mode of processing in the condition with bivalent stimuli. This observation suggests that even individuals who usually show a preference for overlapping processing at a task level as a default are not entirely immune to crosstalk effects. The general assumption that a presentation of task-relevant stimuli in an integral manner might have made a difference, would also be in line with results of the study by Hommel (1998). That is, smaller or negative BCEs were reported for fewer participants when they performed the dual-task with an integral stimulus (Experiment 4) compared to more separated task stimulus features (Experiment 3). Apart from this theoretical reasoning, also an insufficient sample size could be an issue. While the interaction effect did not become significant in the ANOVA, the additional Bayes analysis performed for the TSWP group × R1-R2 compatibility interaction resulted in a Bayes factor neither clearly favoring the null or alternative. Similarly, the confidence interval around the regression line was relatively large, including a wide range of possible regression slopes.

Thus, based on the data of this first experiment, we cannot completely rule out the existence (or absence) of a difference in BCEs across the TSWP groups (which, descriptively with an effect size of $\eta_p^2 = .05$ and in direct contrast to our expectations, even suggest the possibility of a larger BCE in the group of (semi-)overlappers compared to serials in case of an integral stimulus in the dual-task). To obtain a clearer conclusion for or against the relationship, we therefore increased our sample size in the second experiment in which we also separated the stimuli in the dual-task.

Experiment 2

To address the just raised limitations and possible alternative explanations, two main modifications were implemented in the second experiment. First, we increased the sample size. Second, we presented the stimuli in the dual-task in a nonintegral way, to provide a better basis for overlappers to simultaneously maintain both response sets without much crosstalk. For this purpose, we perceptually separated the letter and color task, by presenting the letter stimulus with a short SOA before and spatially next to a colored square (see also Experiment 1 of Ellenbogen & Meiran, 2011).

Method

Participants

A new sample of 80 participants was recruited from the Berlin and Tübingen area based on the same participant pools as in Experiment 1. With such a number of participants, we increased the statistical power for detecting a medium sized group × compatibility interaction (i.e., $\eta_p^2 \geq .06$, Cohen, 1988) to at least $1 - \beta = .95$ ($\alpha = 0.05$). Power calculation was again conducted with G*Power 3.1 (Faul et al., 2009). The dataset of one participant was excluded for having more than 20% errors in one of the single-tasks in the TSWP paradigm. In addition, one task switching block and the corresponding two single-task blocks for another participant were lost within the TSWP paradigm because of computer malfunction. However, this participant still produced a reasonable number of trials and was kept within the sample. Inclusion criteria were the same as in Experiment 1.

Stimuli, Apparatus, and Tasks

Stimuli and apparatus for the TSWP paradigm were identical to those of Experiment 1. The dual-task remained the same apart from the way the stimuli were presented. Instead of an integral stimulus, the stimuli for Task 1 were the letters ‘H’ or ‘S’ presented in white above the center of the screen. Stimuli for Task 2 were red and green rectangles appearing 100 ms after the letter below the center of the screen. Responses were identical to Experiment 1. Thus, participants responded to letters with a left/right manual key press and to the colored squares with a left/right pedal press.

Procedure

Procedural aspects for the TSWP paradigm were identical to Experiment 1. The only change made within the dual-task was that participants now worked on twelve (instead of ten) experimental blocks.

Design and Analyses

Data analyses generally followed that of Experiment 1. For the TSWP paradigm, 3.37% and 3.47% of the trials were excluded as outliers for the digit and letter task, respectively. The percentages of outliers for the dual-task were 2.82% and 3.06% for Task 1 and 2, respectively. The IRI cut-off value was set to 150 ms for the dual-task.

Results

Based on the distribution of fast switch rates, 40 participants were classified as overlappers, 10 as semi-overlappers, and 29 as serials (see again the Appendix for more information).

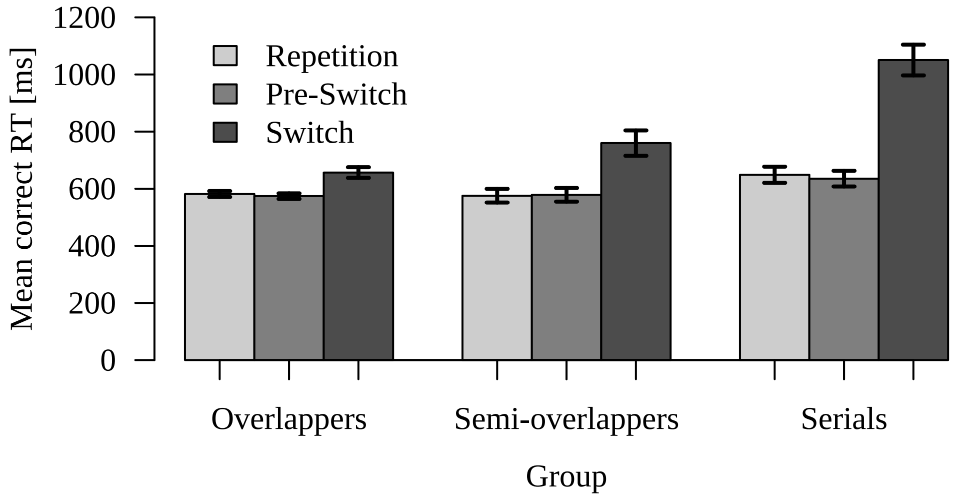
TSWP

Results of the TSWP paradigm closely mirrored those from the first experiment. Mean correct single-task RTs were 627 ms and 580 ms for overlappers, 617 ms and 577 ms for semi-overlappers, and 712 ms and 660 ms for serials (digit and letter task, respectively). Accordingly, the main effects of group, $F(2, 76) = 21.55$, $p < .001$, $\eta_p^2 = .36$, as well as task, $F(1, 76) = 116.89$, $p < .001$, $\eta_p^2 = .61$, were significant. The interaction was not significant, $F(2, 76) = 0.54$, $p = .587$, $\eta_p^2 = .01$. Less errors were made in the letter task (3.16%, 3.09%, and 2.39% for overlappers, semi-overlappers, and serials, respectively) relative to the digit task (3.93%, 4.38%, and 3.08%, respectively), $F(1, 76) = 21.28$, $p < .001$, $\eta_p^2 = .22$. The main effect of group, $F(2, 76) = 1.32$, $p = .273$, $\eta_p^2 = .03$, and the interaction between group and task were not significant, $F(2, 76) = 0.63$, $p = .537$, $\eta_p^2 = .02$.

Mean correct RTs in the task-switch condition are visualized in Figure 6. RTs again increased from overlappers to semi-overlappers and serials, with serials having the longest overall RTs, $F(2, 76) = 49.04$, $p < .001$, $\eta_p^2 = .56$. RTs were longest for switch trials, while they were similar for repetitions and pre-switches, $F(2, 152) = 189.95$, $p < .001$, $\eta_p^2 = .71$, $\varepsilon = .531$. Again, and as implicated by our classification, this effect was almost absent for overlappers, but apparent for semi-overlappers and serials yielding a significant interaction, $F(4, 152) = 61.99$, $p < .001$, $\eta_p^2 = .62$, $\varepsilon = .531$. An analogous ANOVA on the PEs did not reveal a statistically significant main effect or interaction, group, $F(2, 76) = 0.34$, $p = .711$, $\eta_p^2 = .01$; trial type, $F(2, 152) = 1.31$, $p = .274$, $\eta_p^2 = .02$; trial type × group, $F(4, 152) = 0.70$, $p = .593$, $\eta_p^2 = .02$.

Figure 6

Mean Correct RTs of the TSWP Paradigm as a Function of Trial Type in Task Switching Blocks and TSWP group (Experiment 2)



Note. Error bars are 95% confidence intervals after removing inter-subject variability (Morey, 2008), calculated separately for each group.

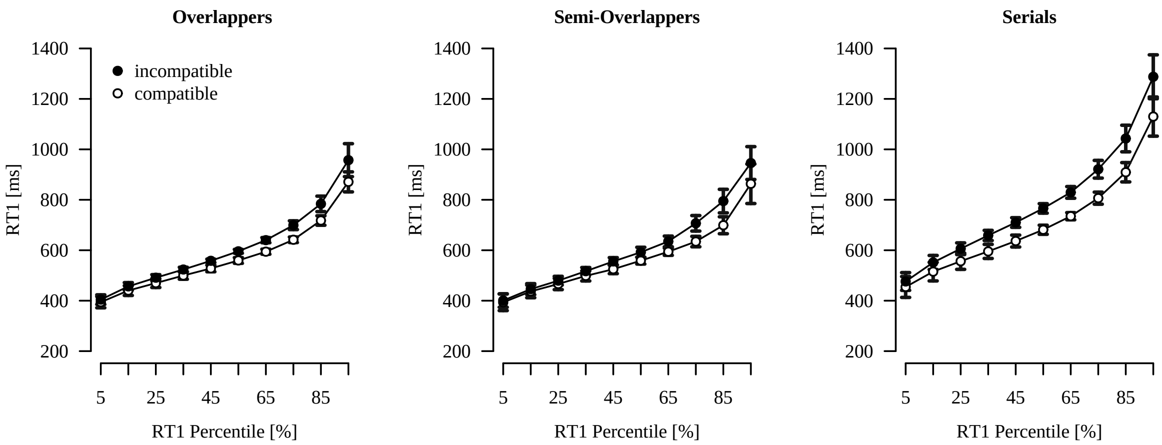
Dual-Task

Mean correct Task 1 RT percentiles are visualized in Figure 7. Responses were slower with higher percentiles, $F(9, 684) = 354.45$, $p < .001$, $\eta_p^2 = .82$, $\varepsilon = .124$, and were overall faster in R1-R2 compatible (619 ms) relative to incompatible (674 ms) trials, $F(1, 76) = 40.13$, $p < .001$, $\eta_p^2 = .35$, thus a BCE was present. This BCE was larger with slower responses, reflected by a significant interaction of R1-R2 compatibility and percentile, $F(9, 684) = 18.26$, $p < .001$, $\eta_p^2 = .19$, $\varepsilon = .159$. Serials produced a larger amount of slow responses and displayed a wider distribution than semi-overlappers or overlappers, indicated by a significant main effect of group, $F(2, 76) = 11.62$, $p < .001$, $\eta_p^2 = .23$, and a significant interaction between group and percentile, $F(18, 684) = 8.96$, $p < .001$, $\eta_p^2 = .19$, $\varepsilon = .124$. In contrast to Experiment 1, the BCE was smaller for overlappers (39 ms) and semi-overlappers (40 ms) compared to serials (83 ms), indicated by a significant interaction between group and R1-R2 compatibility, $F(2, 76) = 4.19$, $p = .019$, $\eta_p^2 = .10$.[4] The three-way interaction between group, R1-R2 compatibility, and percentile, on the other hand, was not significant, $F(18, 684) = 1.10$, $p = .352$, $\eta_p^2 = .03$, $\varepsilon = .159$. Thus, overlappers and semi-overlappers showed a significantly smaller BCE than serials, but the relative increase of this BCE was comparable for all groups.

[4] The Bayes factor for the interaction between group and R1-R2 compatibility indicated strong evidence for the alternative, $BF_{01} = 0.00018$.

Figure 7

Mean Correct Task 1 RTs of the Dual-Task as a Function of R1-R2 Compatibility, TSWP Group, and RT Percentile (Experiment 2)



Note. Error bars are 95% confidence intervals after removing inter-subject variability (Morey, 2008), calculated separately for each TSWP group.

Because serials (again) produced longer RTs than (semi-)overlappers, we conducted an analogous ANOVA on the log-transformed RTs in Task 1. The transformation did not change any outcome of the ANOVA: percentile, $F(9, 684) = 1100.61$, $p < .001$, $\eta_p^2 = .94$, $\varepsilon = .146$; R1-R2 compatibility, $F(1, 76) = 53.61$, $p < .001$, $\eta_p^2 = .41$; group, $F(2, 76) = 10.19$, $p < .001$, $\eta_p^2 = .21$; R1-R2 compatibility × percentile, $F(9, 684) = 15.71$, $p < .001$, $\eta_p^2 = .17$, $\varepsilon = .200$; group × percentile, $F(18, 684) = 3.86$, $p = .015$, $\eta_p^2 = .09$, $\varepsilon = .146$; group × R1-R2 compatibility; $F(2, 76) = 3.35$, $p = .040$, $\eta_p^2 = .08$; group × R1-R2 compatibility × percentile, $F(18, 684) = 0.86$, $p = .482$, $\eta_p^2 = .02$, $\varepsilon = .200$. To determine specific group differences, we conducted a set of exploratory post-hoc ANOVAs on the log-transformed RTs with the factors of group and R1-R2 compatibility. The corresponding interaction reached statistical significance only when considering the groups of serials and overlappers, $F(1, 67) = 6.21$, $p = .015$, $\eta_p^2 = .08$, but not when considering serials and semi-overlappers, $F(1, 37) = 1.64$, $p = .208$, $\eta_p^2 = .04$, or semi-overlappers and overlappers, $F(1, 48) = 0.09$, $p = .772$, $\eta_p^2 < .01$. Similar ANOVAs on the untransformed RTs came to the same conclusions.

Mean Task 1 PEs are summarized in Table 2. More errors were committed in R1-R2 incompatible compared with compatible trials, $F(1, 76) = 11.33$, $p < .001$, $\eta_p^2 = .31$. The main effect of group, $F(2, 76) = 0.06$, $p = .940$, $\eta_p^2 < .01$, as well as the interaction between group and R1-R2 compatibility were not statistically significant, $F(2, 76) = 0.63$, $p = .535$, $\eta_p^2 = .02$.

Table 2

Mean PEs of Tasks 1 and 2 of the Dual-Task as a Function of R1-R2 Compatibility and TSWP Group (Experiment 2)

	Task 1			Task 2		
	Compatibility			Compatibility		
TSWP Group	Incompatible	Compatible	Δ	Incompatible	Compatible	Δ
Overlappers	2.1	1.0	1.1	3.3	3.9	-0.6
Semi-Overlappers	2.1	1.2	0.9	4.7	3.8	0.9
Serials	2.0	1.4	0.6	3.4	4.6	-1.2

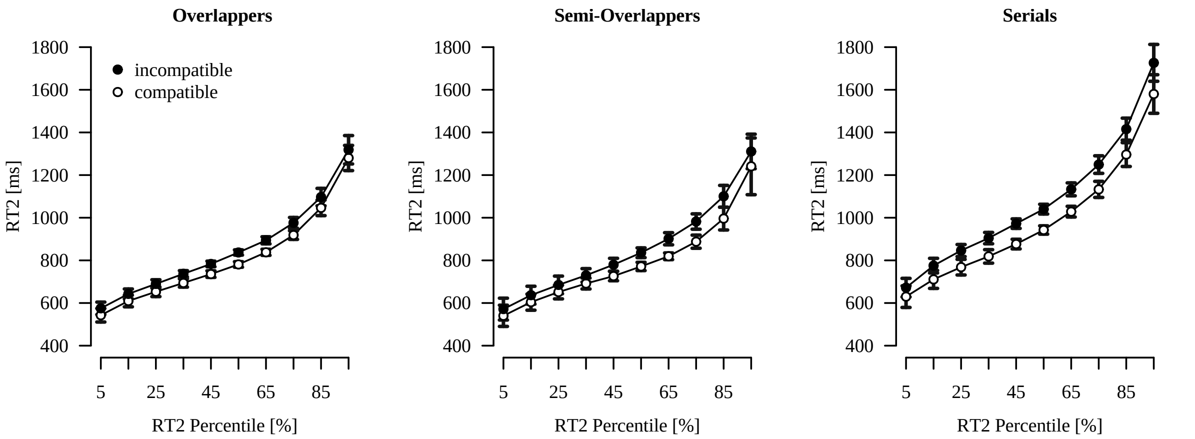
Note. Δ = difference between compatible and incompatible trials, that is, the crosstalk effect within the respective TSWP group.

Mean correct Task 2 RT percentiles are visualized in Figure 8. Responses were slower with higher percentiles, $F(9, 684) = 434.11$, $p < .001$, $\eta_p^2 = .85$, ε = .132, and overall faster in R1-R2 compatible (870 ms) relative to incompatible (935 ms) trials, $F(1, 76) = 48.19$, $p < .001$, $\eta_p^2 = .39$, and this difference became larger with slower responses, $F(9, 684) = 5.31$, $p = .006$, $\eta_p^2 = .07$, ε = .217. Serials generally responded slower and displayed a wider RT distribution compared to overlappers or semi-overlappers, reflected by a significant main effect of group, $F(2, 76) = 15.26$, $p < .001$, $\eta_p^2 = .29$, and a significant interaction between group and percentile, $F(18, 684) = 7.84$, $p < .001$, $\eta_p^2 = .17$, ε = .132. Parallel to the RT analysis of Task 1, overlappers and semi-overlappers showed a smaller compatibility effect (45 ms and 60 ms) than serials (95 ms), $F(2, 76) = 4.02$, $p = .022$, $\eta_p^2 = .10$, but the relative increase of this compatibility effect with slower responses did not differ reliably between groups, $F(18, 684) = 1.52$, $p = .200$, $\eta_p^2 = .04$, $\varepsilon = .217$.

An analogues ANOVA on the log-transformed RT2s revealed all main effects to be (still) statistically significant: percentile, $F(9, 684) = 911.38$, $p < .001$, $\eta_p^2 = .92$, $\varepsilon = .148$; R1-R2 compatibility, $F(1, 76) = 65.70$, $p < .001$, $\eta_p^2 = .46$; group, $F(2, 76) = 14.30$, $p < .001$, $\eta_p^2 = .27$. However, in contrast to the untransformed RTs, none of the interaction terms reached the conventional level of statistical significance: R1-R2 compatibility × percentile, $F(9, 684) = 2.01$, $p = .126$, $\eta_p^2 = .03$, $\varepsilon = .273$; group × percentile, $F(18, 684) = 2.03$, $p = .121$, $\eta_p^2 = .05$, $\varepsilon = .148$; group × R1-R2 compatibility, $F(2, 76) = 2.67$, $p = .076$, $\eta_p^2 = .07$; group × R1-R2 compatibility × percentile, $F(18, 684) = 1.30$, $p = .268$, $\eta_p^2 = .03$, $\varepsilon = .273$. Thus, differences in the compatibility effect between TSWP groups were no longer reliable after controlling for different RT2 levels.

Figure 8

Mean Correct Task 2 RTs of the Dual-Task as a Function of R1-R2 Compatibility, TSWP Group, and RT Percentile (Experiment 2)



Note. Error bars are 95% confidence intervals after removing inter-subject variability (Morey, 2008), calculated separately for each TSWP group.

Mean PEs in Task 2 are summarized in Table 2. Surprisingly, the descriptive values of the compatibility effect for overlappers and serials were slightly negative, indicating that more errors occurred in R1-R2 compatible compared with incompatible trials. However, none of the effects were statistically significant: group, $F(2, 76) = 0.32$, $p = .727$, $\eta_p^2 = .01$; R1-R2 compatibility, $F(1, 76) = 0.41$, $p = .521$, $\eta_p^2 = .01$; group × R1-R2 compatibility, $F(2, 76) = 1.33$, $p = .270$, $\eta_p^2 = .03$.

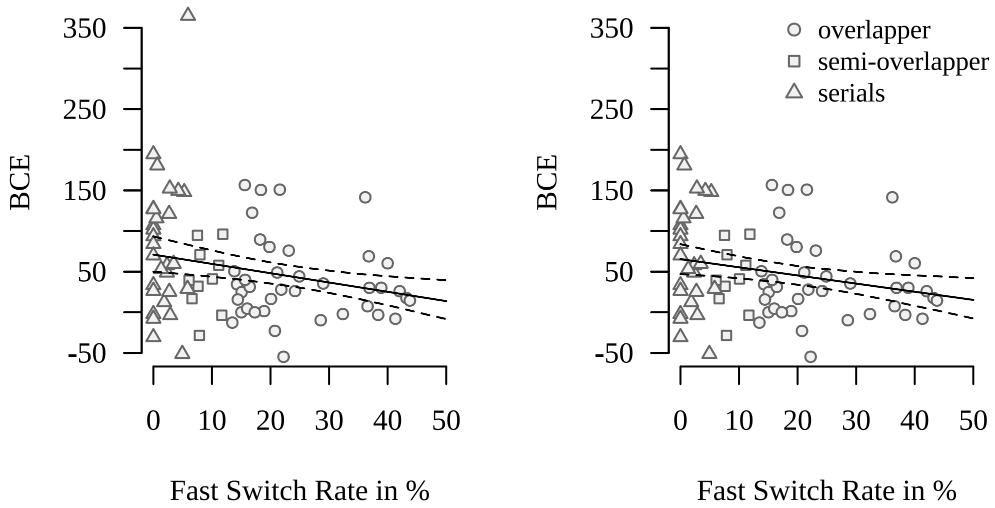
Regression Analysis

Similar to Experiment 1, we performed a generalized-least squares regression with the fast switch rate as the predictor and the individual BCE values as the criterion to avoid the information loss accompanying the classification. A scatter plot of the raw data and the estimated regression line is presented in Figure 9 (left panel). Identical to the conclusions inferred from the ANOVA results, there was a significant relationship, with higher fast switch rates indicating smaller BCEs, $t(77) = -2.58$, $p = .012$, $\beta = -1.15$. Taking a closer look at the left panel of Figure 9, one may object that one participant depicted a very large BCE which might distort the regression. Excluding the corresponding participant, however, kept the results nearly unchanged, $t(76) = -2.42$, $p = .018$, $\beta = -1.00$ (see Figure 9, right panel).[5] Analogous to Experiment 1, there was again a subset of participants who depicted a negative BCE (approximately 20%).

[5] Performing the regressions (i.e., with and without the outlier) on the log-transformed RT1s also left the relationship unchanged: with the outlier, $t(77) = -2.37$, $p = .020$, without the outlier, $t(76) = -2.19$, $p = .031$. Note, however, that when the ANOVA from the previous section was repeated without the outlier and log-transformed RT1s, the group × R1-R2 compatibility interaction did no longer reach the conventional level of significance, $F(2, 75) = 2.46$, $p = .092$, $\eta_p^2 = .06$, likely due to the informational loss accompanying the classification. With untransformed RT1s, the interaction was still significant though, $F(2, 75) = 3.24$, $p = .045$, $\eta_p^2 = .08$.

Figure 9

Individual Mean BCE Values Within the Dual-Task as a Function of the Respective Fast Switch Rates in the TSWP Paradigm (Experiment 2). The Left Panel Includes an Outlier (Upper Left Corner), the Right Panel Excludes the Outlier



Note. The solid black line is the fitted regression line. The curved and dashed lines depict the upper and lower boundary of a 95% bootstrapped confidence interval.

Discussion

In Experiment 2, we collected data from a larger sample and used a dual-task with separated Task 1 and Task 2 stimuli to address aspects of Experiment 1 that may have worked against observing a relation between parallel processing on the task and on the stage level.

Similar to Experiment 1, all TSWP groups indicated signs of crosstalk in the dual-task and the increase of this crosstalk with longer RTs was comparable between groups. However, in Experiment 2, the TSWP groups differed significantly in their overall size of the BCE, with those who engage into a more overlapping relative to serial processing mode at a task level showing a smaller BCE.[6] Even after controlling for differences in response speed by an

[6] A reviewer suggested that differences in coupling one's motor response might explain our results. Indeed, if serials relative to (semi-)overlappers integrate their responses, larger BCE values might be a natural consequence. To exclude this explanation, we binned each individual's IRIs into five equally spaced bins and performed an ANOVA with the factors TSWP group, R1-R2 compatibility, and IRI bin. Neither the two-way interaction between group and IRI bin, nor the three-way interaction between group, R1-R2 compatibility, and IRI bin, turned out to be statistically significant, $F(8, 304) = 0.64$, $p = .671$, $\eta_p^2 = .02$, and, $F(8, 304) = 0.63$, $p = .730$, $\eta_p^2 = .02$, respectively. Descriptively, (semi-)overlappers actually exhibited smaller IRIs than serials (353

additional analysis of log-transformed RTs, this effect was still reliable in RT1 (except when considering the ANOVA approach after excluding an outlier). Thus, Experiment 2 in comparison to Experiment 1 indeed suggests a relation between overlapping processing at the task level and lower susceptibility to interference at the stage level.

General Discussion

The purpose of the present study was to shed light on how individual preferences for serial versus (semi-)overlapping processing on the level of entire tasks are related to inter-individual differences on the stage level indicated by the size of the BCE. In two experiments, we identified individual preferences for a more overlapping or more serial processing mode using the fast switch rate within the TSWP paradigm. Based on this fast switch rate and the according classification, we then compared the individuals' mean BCEs in a dual-task. In Experiment 1, stimuli for the dual-task were presented in an integral way involving a relatively high risk of crosstalk (see Ellenbogen & Meiran, 2011). As this degree of crosstalk might have masked differences between the TSWP groups, the stimuli in the dual-task were presented separately and with a short SOA to reduce the overall risk of crosstalk in Experiment 2. In this case, systematic differences in the BCE between the TSWP groups became apparent. More precisely, a smaller BCE was shown by participants preferring an overlapping compared to a serial mode of processing in the TSWP paradigm, a difference also mirrored in the additional regression analysis. This latter effect suggests that indeed a link exists between the preferred mode of processing on the task level and the vulnerability to interference effects induced by parallel processing on a stage level.

Shared Central Capacity Versus Vulnerability to Interference

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ms, 349 ms, and 399 ms, for overlappers, semi-overlappers, and serials on average, respectively). This fits well with results reported by Brüning et al. (2021), that is, (semi-)overlappers are more likely to integrate their motor responses in a free concurrent dual-task.

Before accepting this conclusion, however, we need to elaborate on another way to interpret the BCE. For example, it seems to be a fair point to argue that the BCE does not reflect the vulnerability to interference effects caused by parallel processing, but rather the amount of shared central capacity (i.e., the extent of parallel processing at the central stage), which is to some extent under voluntary control (e.g., Lehle & Hübner, 2009). Indeed, such an interpretation would follow from a strict interpretation of related models in the context of dual-tasking (Navon & Miller, 2002; Tombu & Jolicœur, 2003). However, if this was the case, and if individual preferences were stable across the stage and task level, we would have expected serials to show a smaller BCE than (semi-)overlappers. This is because those who avoid pre-processing an upcoming task on the task level should be those who try to “actively and efficiently counteract their automatic-translation processes” (Hommel, 1998, p. 1378) on the stage level (i.e., serialize their central stages). Yet, there was hardly any reliable evidence for this in Experiment 1, and Experiment 2 actually demonstrated the reverse pattern. Thus, sticking with the interpretation that the BCE mainly indicates the amount of shared resources, we would have to explain a larger BCE for serials than (semi-)overlappers by assuming that each group switches their preferences for a certain mode of processing as a function of the paradigm. Although this alternative interpretation, in principle, cannot be ruled out based on the data of our experiments, it at least seems to be highly unplausible to us.

As a consequence, we propose that it is easier to interpret our results in terms of inter-individual differences in the vulnerability for task interference at the central stage of response selection than in terms of differences in strategies. Such an argument would also consider the characteristics of the two paradigms. TSWP offers options for strategic process organization in terms of serial versus overlapping processing on the task level (e.g., because there is no immediate deadline for responding to the upcoming task). In contrast, the dual-task used to assess the BCE enforces to share resources between the processes on the central stages of response selection. This might (a) be a result of the rapid and overlapping presentation of task stimuli and (b) of the necessity of responding to both tasks in every trial. Accordingly, individuals might choose a certain mode of processing within TSWP in line with their preference, but not within the dual-task (i.e., serials and (semi-)overlappers alike share their resources within the dual-task). If so, our results would suggest an inability of serials relative to (semi-)overlappers to cope with task interference at the stage level, reflecting a factor with considerable inter-individual differences. In Experiment 1, the risk of crosstalk in the dual-task might have been relatively high for all participants, thereby masking these differences. With stimuli that support a bottom-up separation between tasks in Experiment 2, however, differences in the vulnerability to crosstalk were detectable.

Putting the Stage and Task Level Into Perspective

Based on the above outlined reasoning, we would not assume a direct relationship between the size of an interference effect and the underlying amount of parallel processing (i.e., shared resources) at a certain stage, but instead suggest a conceptual separation of these aspects. That is, parallel processing is mandatory for interference, but is not its sole cause. Although this perspective is uncommon in BCE research, especially concerning the central stage of response selection, it is very common in research on the task level. For example, in more general resource theories (Kahneman, 1973; Navon & Gopher, 1979; Wickens, 1984, 2002) it is assumed that processing resources can be shared and allocated to cognitive processes targeting different tasks without necessarily leading to task interference.

Two possible reasons could account for the fact that (semi-)overlappers are less prone to task interference at the stage level compared to serials. First, previous research has reported differences in working memory capacity between serials and overlappers, with overlappers showing a higher working memory capacity than serials (Brüning & Manzey, 2018). Thus, (semi-)overlappers might just have more working memory capacity to run processes on the central stage in parallel with fewer interference. This interpretation would fit to similar inter-individual differences for Stroop interference effects, which also have been linked to differences in working memory capacity (e.g., Long & Prat, 2002). Alternatively, it could be that (semi-)overlappers differ from serials in fundamental mechanisms enabling them to protect task sets against confusion. For example, they might more easily inhibit prepotent Task 2 responses (see e.g., Friedman & Miyake, 2017).

Regarding the overall goal of this study, that is, attempting to explore a link between the concepts of parallel processing on a stage and task level, our results indicate that both perspectives are related. As just described, individuals appear to differ in their vulnerability to task interference on a central stage of response selection. We tentatively suggest that these inter-individual differences then shape an individual’s potential to cope with the multitasking requirements at the level of processing entire tasks. In case individuals are likely to suffer from emerging task interference, they tend to rely on a more cautious strategy by keeping each task as separated as possible. The result is a serial processing strategy in the TSWP paradigm (i.e., sequential processing on a task level), reflected in pronounced time costs on switch trials (Brüning & Manzey, 2018; Brüning et al., 2021; Reissland & Manzey, 2016). When, in contrast, individuals are less prone to interference on a stage level, they have the cognitive potential to explore options of overlapping processing at a task level. In this case, individuals can choose a more daring overlapping strategy over a cautious serial one (cf., Schumacher et al., 2001) and pre-process the upcoming task in the TSWP paradigm – at least when the circumstances allow it. Evidence for this might be found in research on introspection. In fact, there is evidence that in some conflict tasks and the dual-task participants can give valid introspective estimations of their RTs, which might be associated with a specific feeling of conflict or an "urge-to-err" (Morsella et al., 2009; Questienne et al., 2018; see also Bratzke & Janczyk, 2021). Thus, if individuals are more or less prone to interference on a stage level, and if they have a subjective feeling for that interference, it is not far-fetched to assume that this leads to a more serial or parallel processing mode at a task level.

A Caveat and Future Directives

While the present study could provide some insights into whether there are inter-individual differences at the stage and task level, there are, of course, limitations. One of the major drawbacks is the conclusiveness of the present study concerning the changes implemented from Experiment 1 to Experiment 2. As mentioned earlier, the bottom-up separation of the dual-task stimuli in Experiment 2 was intended to reduce the risk of task interference relative to the integral stimulus presentation used in Experiment 1. Yet, the average BCE values within each experiment were quite similar (i.e., 51 ms vs. 55 ms for Experiment 1 and 2, respectively). One could thus argue that the risk of task-interference was actually equivalent, challenging our interpretation that the smaller BCE for (semi-)overlappers relative to serials found in Experiment 2 is related to our manipulation (i.e., the "lower risk of crosstalk"). Note, however, that the nonintegral vs. integral way of presenting the dual-task stimuli has previously proven to indeed effectively reduce the risk of crosstalk (Ellenbogen & Meiran, 2011). Besides, the two experiments used samples with different participants, rendering a direct comparison of absolute numbers somewhat problematic and only quasi-experimental. Nevertheless, this is an issue that one has to be aware when treating the results of the present study.

Apart from this, whether a difference in the BCE is only observable with lower risks of crosstalk or not, seems to be of minor importance to the present study's overarching goal, though. To us, it seems more crucial to have demonstrated a relationship at all, thereby providing novel insights on individual multitasking limitations and how this might shape an individual's behavior across paradigms.

Against this background, directives for future research are straightforward. Most notably, although we have shown a relationship between processing tendencies at a task and stage level, there is room for specifying the exact mechanisms within and across them. For example, it is unclear which processing stages are involved in overlapping processing in the

TSWP paradigm: Overlapping processing could take place during the perceptual encoding of task stimuli only, or also during the central stage and the execution of motor programs. Similarly, it is unclear how exactly we can think of the lower vulnerability for task interference of (semi-)overlappers within the dual-task. One way to approach this might be to go beyond mean RTs and accuracy by means of computational modeling. For instance, we might want to fit drift diffusion models (Ratcliff, 1978) to gain deeper insights into the processes or strategies that separate those who pre-process the upcoming task in the TSWP from those who avoid it. Such diffusion models have already been successfully applied to classical task switching paradigms (e.g., Schmitz & Voss, 2012) and are able to disentangle the processes that underly empirical response pattern (i.e., disentangle the contribution of central and non-central processes as well as the influence of response caution). Similarly, Koob et al. (2021) have recently extended the diffusion model for conflict tasks (Ulrich et al., 2015) in a way that it could describe both Task 1 and Task 2 data in a dual-task. Applying the respective model for each individual might specify how (semi-)overlappers differ from serials at the central stage of response selection. Finally, future research could clarify the exact relation between individually preferred task processing modes, vulnerability to task interference, and fundamental cognitive differences in working memory capacity. Thereby, we would be able to connect different multitasking paradigms and embed them within a more fundamental architecture of human information processing.

Conclusion

The present study examined the link between an individual's vulnerability to task interference at the central stage of response selection and an individual's preference for a more serial or overlapping processing mode of entire tasks. Individuals' vulnerabilities to task interference were assessed by the BCE in a dual-task (Hommel, 1998). Individuals' preferences for a more serial or overlapping processing mode of entire tasks were assessed with the TSWP paradigm (Reissland & Manzey, 2016). On each level, our results demonstrate and replicate inter-individual differences. More importantly, however, our results suggest that those individuals who adopt a more overlapping relative to serial processing mode at the level of entire tasks are less prone to task interference at the central stage of response selection.

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Appendix: Classification

In this Appendix, we shortly summarize the rationale for classifying individuals with the TSWP paradigm. As introduced in the design and analyses section of Experiment 1, the critical measure is the fast switch rate. Figure A illustrates the classification procedure for the 43 and 79 participants analyzed in Experiment 1 and 2. In the leftmost distribution of each panel, the percentages of fast switches of 48 participants are depicted, which were assessed during a classical task switching (CTS) condition (i.e., without a preview) within the study by Brüning and Manzey (2018). Note that the data assessed in the CTS condition were analyzed as the data were analyzed in the TSWP condition (e.g., with respect to outliers). Here, participants switched between classifying letters as to whether their pronunciation includes an “e” or not and classifying digits as larger or smaller than 5. Furthermore, responses were given manually and participants worked on three experimental runs, each comprising a 120 seconds task switching block and two subsequent 60 seconds single-task blocks.[7] Importantly, in the CTS blocks, only one task’s stimulus at a time was visible. Because indications of overlapping processing in this condition can only occur by chance, it can thus be taken as a reference distribution for serial processing. In TSWP, on the other hand, participants can pre-process the next task’s stimulus, resulting in a distribution that contains larger percentages of fast switches (see the “with preview” conditions in Figure A).

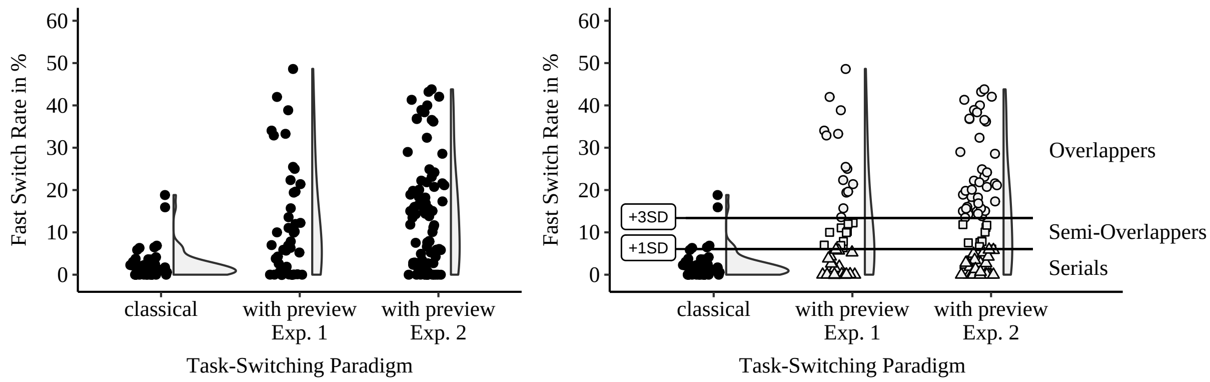
By comparing the percentages of fast switches of the CTS and TSWP conditions, conclusions can be drawn about the respective processing type. This can best be seen in the

[7] One may object that the experimental setup in Brüning et al. (2018) differed from the one considered in the present study. Yet, three considerations may outweigh this concern. First, fast switches and the resulting fast switch rate are relative metrics. That is, switch RTs are compared against single-task performance (of the same task) and the fast switch rate is a proportion based on all correct switches. As such, the speed with which a task can be processed, and the absolute number of switches should only have a minor influence. Second, in a TSWP study with the same experimental setup as in the present study (Reissland & Manzey, 2016), the average fast switch rate under CTS conditions was 2.35% (*SD* = 3.17%), closely mirroring the average fast switch rates in the data set by Brüning and Manzey (2018; *M* = 2.40%, *SD* = 3.67%). Note that the Brüning and Manzey (2018) data were preferred to the Reissland and Manzey (2016) data, because the former included almost thrice as many participants, which better reflects the continuous nature of the data. Finally, and most importantly, avoiding the classification by conducting regression analyses on the full range of fast switches (see the results sections), yielded the same conclusions as those based on the classification.

right panel of Figure A. In case an individual engages in serial processing (i.e., avoids processing the preview), we expect this individual's fast switch rate to be within the range of the fast switch distribution in a CTS condition (i.e., to be below the mean plus one *SD* of the CTS distribution). Conversely, if an individual engages in overlapped processing (i.e., benefits from the preview), we expect their corresponding fast switch rate to be substantially higher (i.e., to be above the mean plus three *SD*s of the corresponding CTS distribution). Participants who fall in between those boundaries are considered (semi-)overlappers.

Figure A

Schematic Outline of the Classification Procedure in the Present Study



Note. Individual fast switch rates in conditions of classical task switching (CTS; *n* = 48, from Brüning & Manzey, 2018) and task switching with preview (*n* = 43 and *n* = 79; from Experiment 1 and 2, respectively) are depicted in each panel. The difference between the two panels is that the right panel additionally contains the classification boundaries (i.e., the mean plus 1 *SD* or plus 3 *SD*s of the CTS distribution) and according processing types. In case a participant in the 'with preview' condition is below the mean plus 1 *SD* of the 'classical' task switching condition, they are considered a serial processor (triangles). In case a participant is above the mean plus three *SD*s, they are considered an overlapping processor (circles). Any participant who falls in between those boundaries is considered a semi-overlapping processor (rectangles).