Flexibility of individual multitasking strategies in task-switching with preview: are preferences for serial versus overlapping task processing dependent on between-task conflict? — Source link

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Flexibility of individual multitasking strategies in task-switching with preview: Are preferences for serial versus overlapping task processing dependent on between-task conflict?

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Abstract

The prevalence and the efficiency of serial and parallel processing under multiple task demands are highly debated. In the present study, we investigated whether individual preferences for serial or overlapping (parallel) processing represent a permanent predisposition or depend on the risk of crosstalk between tasks. Two groups (n = 91) of participants were tested. One group performed a classical task switching paradigm, enforcing a strict serial processing of tasks. The second group of participants performed the same tasks in a task-switching-with-preview paradigm, recently introduced by Reissland and Manzey (2016), which in principle allows for overlapping processing of both tasks in order to compensate for switch costs. In one condition, the tasks included univalent task stimuli, whereas in the other bivalent stimuli were used, increasing risk of crosstalk and task confusion in case of overlapping processing. The general distinction of voluntarily occurring preferences for serial or overlapping processing when performing task switching with preview could be confirmed. Tracking possible processing mode adjustments between low- and high-crosstalk condition showed that individuals identified as serial processors in the low-crosstalk condition persisted in their processing mode. In contrast, overlapping processors split up in a majority adjusting to a serial processing mode and a minority persisting in overlapping processing, when working with bivalent stimuli. Thus, the voluntarily occurring preferences for serial or overlapping processing seem to depend at least partially on the risk of crosstalk between tasks. Strikingly, in both crosstalk conditions the individual performance efficiency was the higher, the more they processed in parallel.

Keywords: individual differences, task processing, task switching, preview, parallel processing, serial processing

Flexibility of individual multitasking strategies in task-switching with preview: Are preferences for serial versus overlapping task processing dependent on between-task conflict?

The tendency to aim for efficient multitasking performance, that is coping with two or more concurrent tasks at the same time or in close succession (Salvucci, 2013), can frequently be observed in our everyday life. For example, we switch rapidly between writing an e-mail and answering a phone call or we listen to the news while driving a car. Comparably, also many multimedia devices demand that we efficiently organize multiple tasks at once or in close succession. But is this task-organization realized by actually performing processing steps of the tasks simultaneously or by rapidly switching between the tasks? And does the task-processing mode represent an individual characteristic or is it flexibly adjusted to the kind of tasks we perform? While the first question involves the basic issue of serial versus parallel processing, the second question addresses the issue of rigidity versus flexibility of individual preferences for these two modes of task-processing.

Thus far, the issues of serial versus parallel processing in multitasking has primarily been addressed in the context of the *psychological refractory period* (PRP) paradigm (for a review, see Fischer & Plessow, 2015). The PRP effect refers to the observation that in dual-tasking the response to the second task is usually the more prolonged the more both tasks overlap in time. The most popular model explaining this effect is the response-selection-bottleneck (RSB) model (Pashler, 1994). According to this model, peripheral processes of perception and response execution can actually be processed in parallel to other processes. However, the central stage of information processing reflecting response selection can handle just one task at a time and, thus, requires a strict serial processing of tasks at this stage if performed in close temporal proximity (Pashler, 1994). Alternative models do not assume such strict structural central limitation of human information processing, but a limitation of the response selection stage in terms of a limited amount of processing resources, which can be flexibly allocated and shared among different tasks (Navon & Miller, 2002; Tombu & Jolicoeur, 2002, 2003; Wickens, 1984, 2002). These latter models allow for parallel as well as serial task processing even at the central stage of response selection, depending on the chosen strategy of resource allocation. Research findings supporting this idea include findings of backward crosstalk (i.e., facilitated performance in a first task, when a subsequent task requires compatible elements; Fischer, Miller, & Schubert, 2007; Hommel, 1998; Janczyk, Pfister, Hommel, & Kunde, 2014; Miller, 2006; Navon & Miller, 1987, 2002; Schubert, Fischer, & Stelzel, 2008) which are at least difficult to explain in terms of a structural limitation. Other findings suggest that serial and parallel processing represent two modes of task-processing, which can be applied with some flexibility, depending on instructions

(Lehle & Hübner, 2009), on task characteristics (Fischer, Gottschalk, & Dreisbach, 2014; Luria & Meiran, 2005), or on the stress state of an individual (Plessow, Schade, Kirschbaum, & Goschke, 2012).

With respect to the efficiency of the two modes of processing there is some consensus that a serial mode of central processing might be of general advantage for multitasking, at least in situations where participants have no degrees of freedom to choose the order of responses, either because of the specific instruction or a sufficiently long stimulus-onset asynchrony (Logan & Gordon, 2001; Miller, Ulrich, & Rolke, 2009). One reason for this superiority of serial processing is the reduction of possible crosstalk effects between the two tasks, because stimulus-response mappings are less prone to confusion (Navon & Miller, 1987).

An attempt to broaden the view on serial and parallel processing in multitasking by addressing it outside of the PRP paradigm has recently been made by Reissland and Manzey (2016, Experiment 1). They extended the issue of serial versus parallel processing to the task switching domain. In the usual task switching paradigms (for a review, see Kiesel et al., 2010) the participants have no option to use a parallel processing strategy and, thus, have to work on two tasks in a strict serial order. In this case the response time (RT) to the first task after a switch is significantly prolonged indicating switch costs. These are usually attributed to a time-consuming process of task-set reconfiguration which partly can only be performed, when the stimulus of the new task is available (Monsell, 2003) and/or effects of task-inertia, that is residual effects of the task performed before (Allport, Styles, & Hsieh, 1994), which add to the time usually needed to respond to the new task (cf. Meiran, 2010). In their task-switching-with-preview (TSWP) paradigm, Reissland and Manzey (2016, Experiment 1) extended this approach by providing options for parallel processing of the two tasks. For this purpose, they adopted the often used alternating runs paradigm of task switching (Rogers & Monsell, 1995), comprising two classification tasks (A and B), which had to be performed in an AAABBBAAA scheme. As a novel feature, this paradigm was combined with an option to preview the stimulus of the task one has to switch to (i.e., the next stimulus of task B is already displayed while the participant is still working on the AAA sequence; see for an early example of a similar approach also Spector & Biedermann, 1976). Providing such preview gives participants the opportunity to at least partly start processing of the task they have to switch to next, while still working on the currently relevant task. Thus, it combines the requirement of task switching with the option of overlapping (parallel) processing usually studied in the PRP paradigm[1]. It was expected that such overlapping processing, if used, would reduce the switch costs compared to the switch costs occurring in an alternating runs

1 Note that, in the PRP literature the term "parallel" processing is used to describe concurrent processing exactly at the central stage of response selection. We prefer to use the term "overlapping" processing to refer to any partial or full concurrent processing of two tasks, which can include all processing stages.

paradigm without preview, or even turn them into switch benefits. The latter would depend on how far the stages of processing the preview stimulus (perception, response selection, response execution) were executed while the ongoing task was performed.

Their results provide evidence that the preview option led indeed to a reduction of switch costs compared to a control group (i.e. a non-preview group), working on the same tasks in a classical alternating runs paradigm of task switching, which enforces serial processing. However, not all participants contributed to this preview effect. Only about one half of the individuals seemed to repeatedly make use of the stimulus preview. This led to negative switch costs (i.e. benefits) in this subgroup in a considerable number of switch trials which reduced their mean switch costs to about 50 ms only, about 200 ms less than in the control group. Remarkably, the RT to task repetitions before the switches was not compensatory prolonged compared to the control group. This suggests that the participants of this subgroup indeed started to process the task they had to switch to, already, while still being involved in processing the currently relevant task. In contrast, the remaining participants of the preview group retained switch costs similar to those observed in the control group. Obviously, they did not use the provided stimulus preview and processed both tasks entirely serially. Note that these individual differences in task-processing modes were not induced by any specific instruction.

This finding confirmed anecdotal observations from the very first set of task switching studies (Jersild, 1927). By displaying series of mixed tasks on printed lists, Jersild (1927) incidentally included an option of a full preview of the next stimulus participants had to respond to. While the majority of participants showed the usual switch costs, others even benefited from task alternations by achieving modest sized switch benefits instead of costs. Jersild assumed that these latter participants already started processing the next task while still executing the response to the other, thus using the incidentally provided preview for overlapping task processing. Also in the PRP literature hints to systematic individual differences with respect to serial versus parallel processing modes can be found. Schumacher et al. (2001) trained eleven participants with a PRP task by presenting both tasks simultaneously without prescribing a certain order of responses (Experiment 3). Due to this training, the mean PRP effect was considerably reduced to about 80 ms. However, this reduction was only due to a subgroup of five participants for whom the mean PRP effect diminished to a negligible degree (14 ms), pointing to almost perfect dual-task performance. The remaining participants still showed a substantial PRP effect even after training. Schumacher et al. assumed that this difference reflects personal preferences for either a “daring strategy” of task processing, characterized by a “great deal of processing overlap” (p. 107), or a “cautious strategy” reflecting a more serial processing mode.

Altogether these findings add a new perspective on the issue of serial and overlapping processing in multitasking. Findings from the PRP paradigm already show that serial and parallel processing on central processing stages in multitasking are not mutually exclusive but seem to reflect strategic choices. Beyond that, the available data from the TSWP paradigm suggests that individuals differ principally in their "natural" preference for a serial or overlapping processing of entire tasks. Moreover, the results from the TSWP paradigm suggest that overlapping processing is not necessarily less efficient than serial task processing in multitasking. Conversely, its results show that the overlapping processing mode, when used in the TSWP paradigm, is significantly more efficient than serial processing in reducing time-losses at task switches.

However, the study by Reissland & Manzey (2016) does not yet allow to infer, whether these individual preferences are a permanent predisposition or not. A preference for the serial task-processing mode might be explained by a strong tendency for task shielding, which helps avoiding possible issues of crosstalk between two tasks, especially, when the stimuli of the tasks are concurrently available. Nevertheless, in the study by Reissland and Manzey serial processing was used by a considerable percentage of participants although the risk of crosstalk between two tasks was relatively low due to the use of well-distinguishable univalent task stimuli and unambiguous stimulus-response mappings. Thus, it seems to be a sort of conservative multitasking strategy that prioritizes risk avoidance and a clear structure of task-processing over performance maximization. This would correspond to the "cautious" strategy described by Schumacher et al. (2001). However, regarding the preference for overlapping processing the answer is less clear-cut. Here, two alternative explanations might apply: (1) The participants might have intentionally chosen this processing mode in order to optimize their multitasking performance. In this case, they would have accepted the comparatively low risk of possible crosstalk between the two tasks to organize the task switching process as fast as possible. Such a processing mode would correspond to the "daring" strategy of task-processing in PRP tasks described by Schumacher et al. (2) Alternatively, the participants might have simply been unable to shield the two tasks against each other, thus, processed the information provided by the preview involuntarily. For example, it has been suggested that in case of a comparatively low load of perceptual information both, task relevant as well as task irrelevant information will be processed within the bounds of an individual's perceptual capacity (Lavie, 1995, 2010). Thus, participants possessing a higher capacity might naturally be more prone to distractor effects by concurrent task stimuli than others. In case of minimized crosstalk between the tasks this incidental side-effect might have led to performance advantages in terms of time savings at switches, which turned the usual switch costs actually in switch benefits.

Based on that, the aim of the current study is to shed light on the issue to what extent preferences for serial versus overlapping processing reflect a permanent and somewhat rigid predisposition versus an individual's strategic choice in the face of different task characteristics. Based on the TSWP paradigm, we compared two conditions varying in their degree of risk of crosstalk between the two tasks and accordingly in their degree of suitability for either of the processing modes. In order to manipulate the risk of crosstalk we varied the "valence" of the stimulus material. While in one part of the experiment univalent stimuli were used for the two classification tasks to be performed according to the TSWP paradigm, bivalent stimulus material was applied for both tasks in another part. Since bivalent stimuli are task-unspecific, they bear increased risk of crosstalk in terms of confusion of stimulus-response mappings, when processed in an overlapping manner. Accordingly, we expected all participants applying the serial processing mode with univalent stimuli to apply this mode also in case of bivalent task stimuli, which even more require efficient task-shielding due to increased risk of crosstalk. As a consequence of the task-shielding, they should not exhibit any mixing costs, that is, the phenomenon that RTs are higher in task repetitions in mixed blocks than in single task blocks (see, e.g., Los, 1996). However, due to the fact that they do not make use of the preview option, the serial processors should still show considerable switch costs directly comparable to those, which usually arise in classical task switching paradigms with univalent and bivalent stimuli. This also should result in a low overall multitasking efficiency, reflected in less correct responses in alternating compared to single-task performance as measured by the overall dual-task performance efficiency (ODTPE) measure (see the appendix for a detailed description). Regarding the overlapping processors, the considerations mentioned above lead to two clearly distinct expectations. According to the hypothesis of a flexible adaptation of the task-processing mode, we hypothesized that a considerable number of individuals applying overlapping processing in case of less risk of crosstalk (univalent task stimuli) would change to a more serial processing mode allowing for better task-shielding in response to bivalent stimuli. As a consequence, this subgroup should show a better multitasking efficiency in terms of lower switch costs (i.e. benefits due to a preview effect) and higher ODTPE scores than serial processors in the condition with less risk of crosstalk, but essentially the same multitasking efficiency as serial processors in the condition with high risk of crosstalk. Only individuals who are able to practice overlapping processing effectively even in the face of considerable risks of crosstalk should stay with this mode independent of the stimulus valence and, thus, outperform serial processors with respect to multitasking efficiency in both conditions. However, if the observed preference for an overlapping processing mode is a fixed predisposition leading to an involuntary processing of the preview stimulus, the overlapping processors should not be able to adjust their task processing to a more serial mode in case of higher risks of crosstalk. In this case, performance of the overlapping processors should decline with increased risk of crosstalk, reflected not only in high switch costs but also in considerable mixing costs, and an overall low multitasking efficiency.

Another question not yet addressed in previous research regards possible individual preconditions associated with preferences for either of the two processing modes. Individual differences in the extent of working memory capacity (WMC) could be one apparent candidate as it has been shown to affect different aspects of executive functions and attentional control (Engle, 2002; Engle & Kane, 2003; Kane, Conway, Hambrick, & Engle, 2007). Since overlapping processors need to hold and manipulate an additional task stimulus in their working memory while still working on another task, the extent of using the preview option for overlapping processing might depend on the WMC of an individual. If this is the case, a smaller WMC would also severely limit the adaptation of processing mode to different risks of crosstalk. Thus, we expected that individuals with comparatively high WMC make more extensive use of the preview and show more flexibility in their choice of processing mode.

Method

Participants

A total of 96 right-handed volunteers took part in this study. The dataset of four participants were excluded from the analysis due to high error rates (ER; > 15%) in at least one of the performed tasks. The dataset of one further participant was excluded, because his mean RT in task pure repetition trials was higher than four standard deviations (SD) above the according group mean. Thus, the final sample included 91 participants (53 female, mean age = 25.2 years, *SD* = 2.9 years, range = 18 – 30 years). All volunteers were native German speakers with normal or corrected-to-normal vision. They received 7 Euro/hour or course credit and an additionally monetary bonus for each correctly answered stimulus.

Tasks

Two pairs of tasks were used for the experiment. The first task pair included a digit categorization task and a letter categorization task. Thus, this pair comprised univalent task stimuli (digits vs. letters) involving a comparatively low risk of crosstalk when performed in mixed blocks. In the digit categorization task, participants were required to decide whether a presented digit was lower or higher than five (1, 2, 3, 4 vs. 6, 7, 8, 9). In the letter categorization tasks presented consonants had to be classified as to whether their co-occurring vowel contained an "e" or not. Target letters were the consonants D, P, T, W[2]. Non-target letters in this task were the consonants H, K, J and Q.

2 Note that the letters ‘D’, ‘P’, ‘T’, and ‘W’ are pronounced [deː], [peː], [teː], and [veː] in German, while the letters ‘H’, ‘K’, ‘J’, and ‘Q’ are pronounced [haː], [kaː], [jɔt], and [kuː].

The second pair of tasks included two categorization tasks based on the same set of letters (A, B, C, E, O, U, X, Z) and, thus, comprised bivalent stimuli, which provide a comparatively high risk of crosstalk when performed in mixed blocks. The first task of this pair required the categorization of a presented letter according to its position in the alphabet (first half: A, B, C, E vs. second half: O, U, X, Z). The second task was to categorize letters into vowels (A, E, O, U) and consonants (B, C, X, Z).

The individual WMC of our participants was assessed by means of the automated operation span task (Ospan, Turner & Engle, 1989; Unsworth, Heitz, Schrock, & Engle, 2005). The task requires participants to solve a series of simple math operations while trying to remember a set of letters (set sizes 3–7), which needed to be recalled at the end of each test trial.

Stimuli and Apparatus

The experimental stimuli were displayed in light grey (RGB = 245, 245, 245; font size = 24 px) on dark grey background (RGB = 90, 90, 90) on an Acer LCD screen (1280 x 1024 px, sampling with 60 Hz). Stimulus presentation and response recording was controlled by a custom-made JAVA software running on an Intel Pentium (2.9 GHz, 8 GB RAM; Windows 7 Pro). Participants responded by pressing predefined letters on a standard keyboard, which were marked with color points for easier recognition. The keys ‘S’ and ‘A’ were used with the index and middle finger of the left hand to respond to one task and the keys ‘K’ and ‘L’ with the index and middle finger of the right hand to respond to the other task. The task-hand assignment was counterbalanced between participants. The Ospan task was presented on the same screen as the experiment using the Psychology Experiment Building Language (Mueller, 2012; Mueller & Piper, 2014).

Procedure

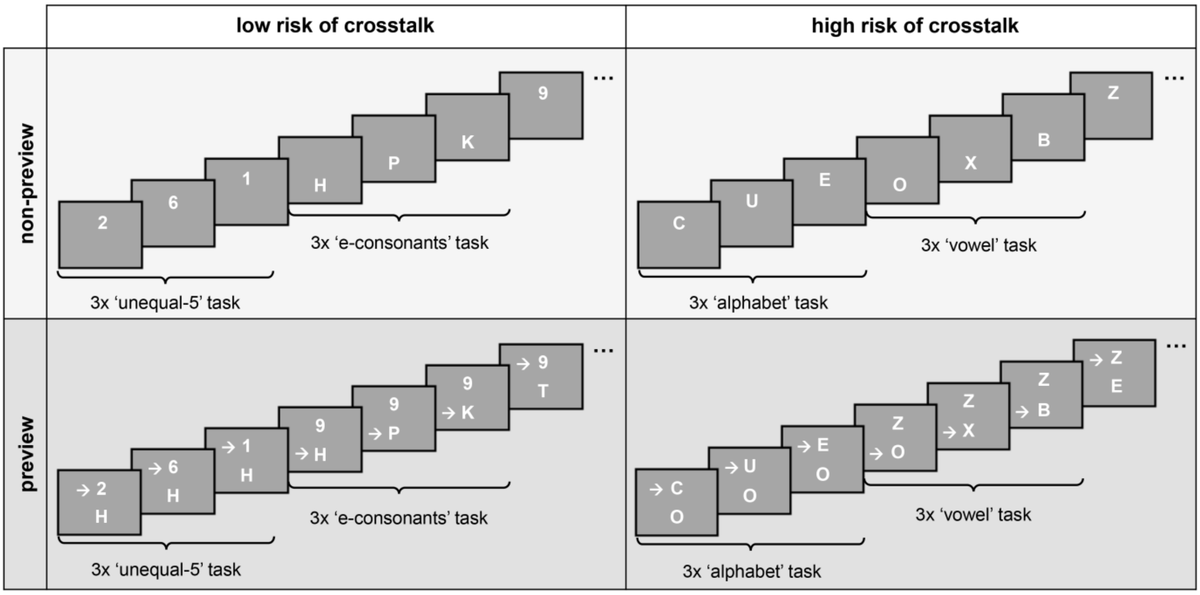
One to four participants were simultaneously tested at independent PC workstations, separated by opaque screens. Each participant performed the Ospan task before the actual experiment was started.

Within two experimental groups (non-preview vs. preview) two crosstalk conditions were performed in counterbalanced order. Instructions for each condition were presented on the computer screen and could be read self-paced. The tasks were structured in fixed time periods and participants were instructed to maximize their amount of correct responses in the given time. First, the according pair of single-tasks was explained including a 30-s block of task familiarization. Subsequently, the participants practiced each single-task for further 60 s to account for initial practice effects. Finally, the respective task switching procedure in mixed blocks was described and practiced for 120 s. The data collection phase then included three runs per condition, each comprising one 120-s mixed block followed by two single-task blocks lasting 60 s, each. The single-task blocks were included in counterbalanced order to control for the stability of single-task performance.

For mixed blocks an alternating run schema (Rogers & Monsell, 1995) of task presentation was used, with both tasks (A and B) of the respective task pair presented in a predictable AAABBB task sequence. With this form of task presentation, four different sorts of trials could be distinguished: single-task trials, pure repetition trials (trials in mixed block which were neither preceded nor followed by a task switch: A***A***AB***B***B), pre-switch trials (trials in mixed blocks, not preceded but followed by a task switch: AA***A***BB***B***) and switch trials (trials in mixed blocks following a task switch directly: ***A***AA***B***BB). The distinction of pure repetition trials and pre-switch trials allowed for an unbiased estimation of mixing and switching costs based on comparisons of RTs for single-task and pure repetitions, and pure repetitions and switch trials, respectively. In addition, the separate consideration of pure repetitions and pre-switch trials enabled for the identification and location of possible crosstalk effects between tasks in mixed blocks with preview.

The scheme of the stimulus presentations in the mixed blocks of the two experimental groups (non-preview/preview) and the two crosstalk conditions is shown in Figure 1.

Fig. 1 Schematic of the classical task switching paradigm (non-preview), and the task-switching-with-preview paradigm (preview) including stimuli inducing low or high risk of crosstalk



The non-preview group always encountered the stimulus of the currently relevant task, only. In order to make the task switches visible also with the bivalent task stimuli in the high-crosstalk condition, the locations of stimulus presentation for the two tasks were separated vertically (distance = 16 px). All task stimuli were shown until a response was recorded. Upon a registered response, the next stimulus appeared immediately (response–stimulus interval = 0 ms).

For the preview group, each mixed block started with the simultaneous presentation of stimuli for both tasks. Corresponding to the non-preview condition the stimuli were presented in vertical arrangement with close spatial proximity, making concurrent perception of the two stimuli possible without eye movements. An external cue (white arrow) supported the participants in following the predictable task switching schedule. The arrow appeared on the left side of the stimulus of the task, which had to be performed first (task A). Upon a response, the next stimulus of this task appeared immediately while the stimulus of the other task (B) remained. Upon the response to the third trial of the currently relevant task (A) in a row, the arrow switched to the stimulus of the other task indicating a task switch. Then the participant performed three trials of the now relevant task B before another switch of the arrow indicated to return to task A and so on. Thus, the participants in the preview group always saw two stimuli, with the stimulus without an arrow providing a preview of the stimulus of the task, which had to be switched to next. This arrangement of stimulus presentation provided the participants of the preview group with the opportunity to apply either a serial or overlapping processing mode of task processing, depending on whether or not they processed the preview-stimulus in an overlapping manner. However, no specific instruction was given concerning these two possible processing modes in the preview group.

The task stimuli of each block were randomly drawn from the stimulus sets of the respective tasks with the constraint that no stimulus would be directly repeated and that the two possible responses per task were equally distributed. At the end of each block the participants were provided with feedback on the number of processed trials and the number and the percentage of correct responses of both tasks for five seconds. Short breaks of one and two minutes were included between the experimental runs of one condition and the two crosstalk conditions, respectively. Altogether the experiment lasted about one and a half hour per participant.

Design

The experiment entailed a 2 (preview vs. non-preview) x 2 (low vs. high crosstalk) x 4 (trial type) design. The first factor represented a between-subjects factor. One half of the sample (preview group, n=45) performed the mixed blocks with the TSWP paradigm, while the second group (non-preview group, n=46) performed the experiment without preview, analog to the classical task switching paradigm. The factor *crosstalk* was manipulated within subjects. All participants performed the two task pairs varying in the degree of risk of crosstalk. The factor *trial type* also represented an independent within-subjects factor, including four trial types: single-task, pure repetition, pre-switch, and switch trials.

Data Analyses

Impact of preview and risk of crosstalk on task switching performance at group level. For each single-task block and the different trial types in mixed blocks the mean RT and ER for each participant were calculated. RTs were in principle determined by the period between stimulus presentation and response. However, in the preview condition the stimulus of a switch trial was always visible before actually requiring a response. Therefore, the RT for switch trials in this group was defined as the time between the change of the cue indicating a task switch and the respective response to the stimulus of the new task. ERs were calculated as the rate of false responses per block. Based on these RT and ER data we further calculated the mean switch and mixing costs for each participant and experimental condition. Switch costs were derived by subtracting the means of RT/ER of pure repetition trials from the means of RT/ER of switch trials. The pure repetition trials were used as reference to prevent influences of a preceding or succeeding switch. Mixing costs were calculated as the difference between means of RT/ER of pure repetition trials in mixed blocks and means of RT/ER of single-task trials. The data of each participant in the different experimental conditions were then collapsed across tasks and experimental runs, yielding 245 single-task trials (SD = 32.9) and 215 mixed block trials (SD = 35.4) per task and participant on average. Trials with an RT slower than two SD from the participant's mean RT in the according block were discarded (5.04% of trials (SD = 0.51%) per participant on average). Only correct responses were considered in the analyses of RTs and measures of efficiency. Based on this data, the first set of analyses addressed the impact of preview and risk of crosstalk on performances at group level. For this purpose, the performance of the preview versus non-preview group in single, repetition, pre-switch and switch trials and both crosstalk conditions were compared. In case of violations of the sphericity assumption, degrees of freedom were corrected according to the Greenhouse-Geisser procedure in all analyses.

Impact of risk of crosstalk on individual preferences for serial versus overlapping processing in the preview group. The data of the participants of the preview group were further analyzed with respect to differences in the applied mode of task processing, which represented the main target of our research. For this purpose, we performed fine-grained analyses of their overtly observable response patterns, inspecting for specific cues for overlapping processing. Two separate analyses were performed for the two crosstalk conditions. Note that the same analyses were also performed for the non-preview group to obtain reference values and that participants of the non-preview group were not further classified whatsoever.

The fine-grained analyses were based on the following logic: Switch trials can be considered to reflect the time needed to process the given task stimulus plus additional time needed for a task-set reconfiguration and/or overcoming possible task-inertia effects from the preceding task (Allport et al., 1994; Monsell, 2003). In case of serial processing, RTs in switch trials are not expected to become as fast as RTs in single-task trials but to reflect some switch costs. In contrast, if we observe switch RTs in the preview condition that are even faster than the typical RTs in single-task trials along with no increase of mixing costs in the repetition and pre-switch trials, this can be taken as clear evidence that at least some processing of the previewed switch stimulus must have taken place already before the switch and, thus, reduced the switch costs to a considerable degree. Based on this rationale, we compared each participant's switch RT on a single-trial basis with the distribution of RTs in the respective single-task condition of this participant. If the RT of a switch trial was in the range of the 25% quickest responses in the single-task or even shorter, the switch was classified as a *fast switch.* Thus, these fast switches are considerably shorter than the mean processing time needed for a single-task response, providing a relatively conservative indicator of overlapping processing cases for each individual.

However, fast switches could also occur by chance, even though a participant works serially on both tasks. In order to estimate this rate of incidentally occurring fast switches the data of the non-preview group was used. Participants of this group had no option for overlapping processing, thus, any fast switches must have occurred incidentally. The classification of the individuals of the *preview* group into subgroups of serial versus overlapping processors was based on a comparison of their individual rate of fast switches with the rates of randomly occurring fast switches derived from the non-preview group. If the mean rate of fast switches of a participant of the preview group fits the range of the random distribution derived from the data of the non-preview group, it cannot be excluded that this participant had worked on the two tasks in a serial manner. Thus, all participants who showed a rate of fast switches that was below the rate corresponding to the grand mean plus one SD of the random distribution, were classified as *serial* processors constituting the *serial subgroup*. Following the same rationale, only participants of the preview group, who showed a rate of fast switches that was higher than the one corresponding to three SDs above the grand mean of the non-preview group, were considered to have worked at least partially in parallel on the two tasks and were classified as *overlapping* processors representing the *overlapping subgroup*. All remaining participants in the preview group were considered to show too many fast switches to occur by chance, but too few to indicate a manifest and clear preference for an overlapping processing mode. Thus, we classified them as *semi-overlapping* processors constituting the *semi-overlapping subgroup*.

Each participant of the preview group was assigned to one of the three subgroups for both the low crosstalk and high crosstalk condition. This procedure enabled to test for systematic changes of the task-processing modes dependent on these two conditions.

Analyses of performance efficiency at subgroup level. Two additional sets of analyses were performed in order to investigate the impact of different modes of processing on performance efficiency in mixed blocks. The first one included comparisons of mean switch costs and mixing costs between the non-preview group and all subgroups of the preview group in both crosstalk conditions. This was done to reveal what sorts of costs or benefits occurred depending on the mode of processing and the given risk of crosstalk. In addition, we compared the multitasking efficiency of the three preview subgroups and the non-preview group in both crosstalk conditions by comparing their overall performance in mixed blocks relative to single-task performance. For this purpose, the ODTPE measure proposed by Reissland and Manzey (2016) was used. It represents a straightforward throughput measure based on the number of correct responses the participants could perform in the given time. Thereby, it allows to describe the overall net efficiency participants achieve in mixed blocks relative to their single-task performance, taking speed and accuracy of responses equally into account. The ODTPE is positively correlated with performance, that is, the higher the ODTPE value, the better the performance in mixed blocks compared to single-task blocks (net benefits: ODTPE > 0). Whereas lower ODTPE values reflect poorer performance in mixed blocks compared to single-task blocks (net costs: ODTPE < 0). A detailed description of this measure is provided in the appendix.

Impact of working memory capacity on preferring different modes of task-processing. A final data analysis addressed to what extent the preferences for serial versus overlapping processing in the low- and high-crosstalk condition were dependent on the individual WMC. For this purpose, all participants of the preview group were categorized as low versus high WMC individuals. This was done based on a median split of the distribution of partial scores achieved by the participants in the Ospan. Since their internal consistency is often reported to be higher compared to the absolute scores, partial scores have been recommended in the literature as the more proper performance measure (Conway et al., 2005; Friedman & Miyake, 2005; Redick et al., 2012). Then, the rate of fast switches as indicators of overlapping processing were compared dependent on WMC.

Results

Effects at Group Level

Table 1 shows the mean RT and ER for the different types of trials, separated for the two experimental groups (non-preview vs. preview) and the two crosstalk conditions (low vs. high crosstalk). We ran a 2 (preview vs. non-preview) x 2 (low vs. high crosstalk) x 4 (trial type) repeated measures ANOVA on RTs. The ANOVA revealed significant main effects of trial type, $F(1.1,102) = 328.25$, $p < .001$, $\eta_p = .79$, and risk of crosstalk, $F(1,89) = 197.89$, $p < .001$, $\eta_p = .69$, as well as a significant interaction between trial type and risk of crosstalk, $F(1.3,111) = 164.99$, $p < .001$, $\eta_p = .65$. Regarding the trial type, Sidak corrected post-hoc pairwise comparisons revealed significant differences between the single and repetition trials ($p = .03$) with shorter RTs in repetitions compared to single trials. In line with this difference, mean mixing costs in repetition and pre-switch trials were very low and negative in almost all conditions. The pairwise comparisons revealed also a significant difference between the switch and all other trials (all $p < .001$; all remaining $p > .24$), indicating that especially the RTs on switch trials compared to the other trial types were considerably prolonged. The latter difference was more pronounced in the high-crosstalk than in the low-crosstalk condition. However, neither a significant main effect of preview, $F(1,89) = 0.05$, $p = .83$, nor significant interaction effects with crosstalk, $F(1,89) = 0.48$, $p = .49$, or trial type, $F(1.1,102) = 0.6$, $p = .46$, or both, $F(1.3,111) = 1.24$, $p = .28$, were found.

ERs were generally low. The corresponding ANOVA for ERs showed a significant main effect of trial type, $F(3,267) = 21.44$, $p < .001$, $\eta_p = .19$, crosstalk, $F(1,89) = 18.25$, $p < .001$, $\eta_p = .17$, and a significant interaction between these factors, $F(2.7,237) = 7.73$, $p < .001$, $\eta_p = .08$. ERs were higher in the high- than in the low-crosstalk condition. For the main effect of trial type Sidak corrected post-hoc comparisons revealed significant differences between the single and all other trials (all $p < .001$; all other $p > .22$), showing that ERs decreased from single-task blocks to mixed blocks. This effect was somewhat more marked in the low- than the high-crosstalk condition. Again, no significant main effect of preview, $F(1,89) = 1.34$, $p = .25$, and no significant interaction effects with crosstalk, $F(1,89) = 0.87$, $p = .35$, or trial type, $F(3,267) = 0.87$, $p = .46$, or both, $F(2.7,237) = 0.25$, $p = .84$ emerged.

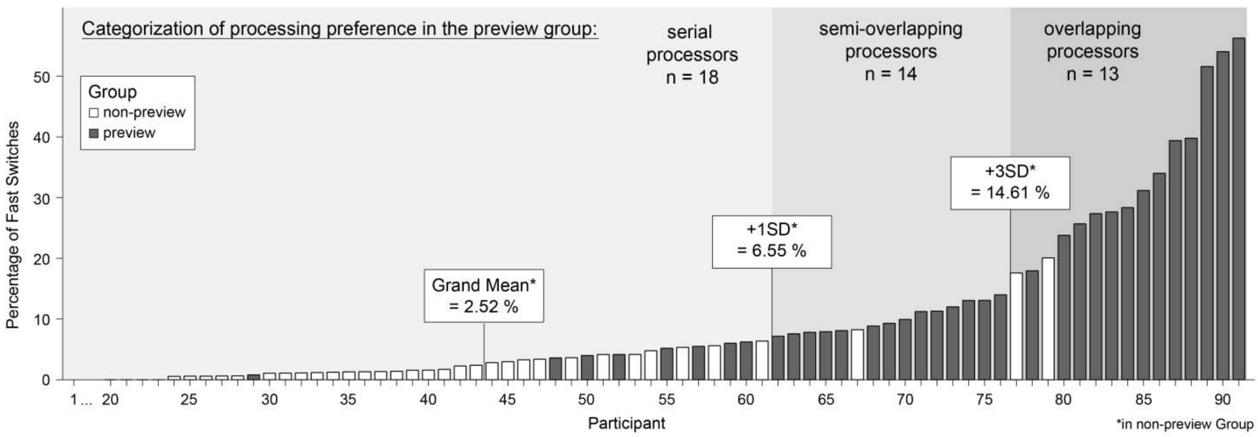
Table 1. Performance, mixing and switch costs by crosstalk condition for the non-preview and preview group: reactions times (RT) in ms, and error rates (ER) in percent.

	Low-crosstalk				**High-crosstalk**			
	Non-preview		**Preview**		**Non-preview**		**Preview**	
Trial type	RT	ER	RT	ER	RT	ER	RT	ER
Single-task	659.8	2.6	648.2	3.0	681.5	2.7	670.6	3.3
Repetition	630.2	1.9	630.4	1.9	676.8	2.0	681.2	2.5
Pre-Switch	623.5	1.8	632.9	1.8	683.2	1.9	688.8	2.2
Switch	825.5	0.8	789.8	1.4	1057.2	2.1	1057.5	2.6
Mixing costs	- 29.6	-0.8	-17.8	-1.1	-4.7	-0.6	10.7	-0.8
Switch costs	195.3	-1.0	159.4	-0.5	380.3	0.0	376.3	0.2

Identification of Individual Modes of Task-Processing in the Preview Group

The distributions of percentages of fast switches for the non-preview and preview group in the low-crosstalk condition are shown in Figure 2. Note that these distributions show the rates of fast switches for each participant of the two groups in ascending order.

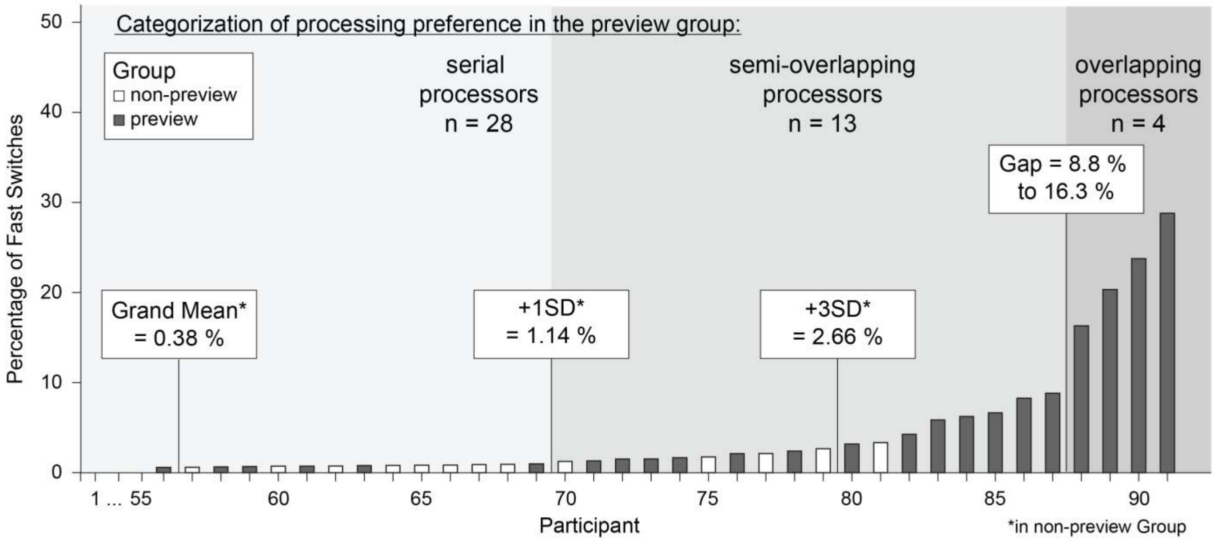
Fig. 2 Distribution of individual rates of fast switches of the non-preview and preview group in the low-crosstalk condition arranged from the lowest to the highest rates. Individuals of the preview group were classified into the three types of processors based on the standard deviation of rates of fast switches in the non-preview group as indicated. Data of 20 individuals showing a rate of exactly 0% fast switches are aggregated as “1...20”. SD = standard deviation. n = number of individuals



As becomes evident, these distributions differed markedly with respect to their mean, albeit with some overlap in range. The rates of fast switches in the non-preview group ranged from 0% to 20.7% (mean (*M*) = 2.52%, *SD* = 4.03%), while the distribution of fast switches in the preview group showed a considerable larger range from 0% to 56.28% (*M* = 14.09%, *SD* = 15.54%). Participants of the preview group who showed a mean fast switch rate not higher than one SD above the grand mean of the non-preview group (6.55%) were considered as individuals who did not make any use of the preview and, thus were classified as *serial processors*. In contrast, those participants in the preview group, who exhibited a fast switch rate of at least 14.61%, that is a rate higher than three SDs above the grand mean of the non-preview group's distribution of fast switches, were categorized as distinct *overlapping processors*. Their rate of fast switches appears clearly too high to be explained just by a random occurrence in case of purely serial processing. Instead they obviously had made repeatedly use of the preview option to start processing the switch task stimulus before the actual switch took place. The remaining individuals occasionally exhibited fast switches reflected in continuous values between 6.55% and 14.61%. While they exhibited too many fast switches to occur just by chance, they did not seem to develop a coherent task-processing mode. Therefore, these individuals were considered as a third distinct subgroup, labeled as *semi-overlapping processors*. Overall, this categorization procedure resulted in three subgroups for the low-crosstalk condition: 18 serial processors (fast switches: *M* = 1.97%, *SD* = 2.53%), 14 semi-overlapping processors (fast switches: *M* = 10.09%, *SD* = 2.33%), and 13 overlapping processors (fast switches: *M* = 35.16%, *SD* = 12.28%).

Figure 3 depicts the corresponding non-preview and preview group's distributions and the according classification of individuals in the preview group in the high-crosstalk condition.

Fig. 3 Distribution of individual rates of fast switches of the non-preview and preview group in the high-crosstalk condition arranged from the lowest to the highest rates. Individuals of the preview group were classified into the three types of processors based on the standard deviation of rates of fast switches in the non-preview group and a marked discontinuation in their own distribution (“gap”) as indicated. Data of 55 individuals showing a rate of exactly 0% fast switches are aggregated as “1...55”. SD = standard deviation. n = number of individuals



Note that both of the latter distributions were more leptokurtic than in the low-crosstalk condition, with a comparatively small range of 0% to 3.34% (*M* = 0.38%, *SD* = 0.76%) of fast switches in the non-preview group, and a somewhat broader range of 0% to 28.8% of fast switches in the preview group (*M* = 3.28%, *SD* = 6.58%). This was expected because the opportunity of identifying overlapping processing based on the rate of fast switches according to our criterion is much more limited in case of bivalent than univalent stimuli. The reason is that participants of both groups (non-preview and preview) can be expected to need more time for task switches in case of bivalent compared to univalent task stimuli, primarily due to task-set inertia adding to the basic costs of task-set reconfiguration (Meiran, 2010). By comparison, the single-task RTs, with which the switch RTs are compared in order to identify fast switches as defined above, are not affected by the valence of the stimuli and, therefore, they remain quick. As a consequence, the a priori probability of observing fast switches is inherently smaller in case of bivalent compared to univalent stimuli, and, thus, the distributions of rates of fast switches must become relatively more leptokurtic for the high-crosstalk than the low-crosstalk condition. Based on these distributions the participants’ mode of processing was initially classified using the same rationale as in the low-crosstalk condition. Thus, individuals showing a rate of fast switches within the range of one SD above the grand mean of the non-preview group, that is less than 1.14%, were classified as serial processors. Applying the same criteria as in the low-crosstalk condition would then have meant to classify all participants with rates of fast switches higher than three SDs above the grand mean of the non-preview group as overlapping processors, and the remaining participants as semi-overlapping processors. However, this classification based on the criteria derived from the very leptokurtic distribution of fast switches in the non-preview condition with a grand mean close to zero would have been somewhat biased, as it would have resulted in a markedly narrow range of the rates of fast switches from 1.14% to 2.66% for the classification of semi-overlapping processors and an overly broadened range of 2.66% to 28.8% fast switches for the classification of overlapping processors. Furthermore, a visual inspection of the whole range of distribution of participants classified as (semi-overlapping or overlapping processors) shows a remarkable discontinuation, characterized by almost a doubling of the rate of fast switches from 8.8% to 16.3%. This clearly visible gap in the distribution of fast switches suggests, that the individuals showing rates of fast switches of 16.3% and higher differ qualitatively from the individuals showing rates of fast switches of 1.14% to 8.8%. In order to take this gap into account, we considered a classification of semi-overlapping and overlapping processors in accordance to this discontinuation as more adequate, instead of just considering the third SD from the grand mean of the distribution of fast switches in the non-preview group. This resulted in the following subgroup sizes in the high-crosstalk condition: 28 serial processors (fast switches: *M* = 0.16%, *SD* = 0.31%), 13 semi-overlapping processors (fast switches: *M* = 4.14%, *SD* = 2.72%), and four overlapping processors (fast switches: *M* = 22.3%, *SD* = 5.3%). Note that the number of participants classified as serial processors was not affected by this procedure.

Changes of task-processing modes between low-crosstalk and high-crosstalk condition. Table 2 shows a cross-table of the frequencies of serial, semi-overlapping and overlapping processors in the low- and high-crosstalk condition. All individuals (n = 18) classified as serial processors in the low-crosstalk condition also used this mode of processing in the high-crosstalk condition. On the contrary, participants working on univalent stimuli in a more overlapping manner, tended to shift to a more serial processing mode in the high-crosstalk condition. Out of the group of 14 semi-overlapping processors in the low-crosstalk condition, only six persisted in their mode, while eight exhibited a serial processing mode of processing in the high-crosstalk condition. Out of the 13 individuals preferring an overlapping processing mode in the low-crosstalk condition, seven were classified as semi-overlapping processors in the high-crosstalk condition, and two turned out to use a distinct serial processing mode, when working with bivalent stimuli. Remarkably, four out of the overlapping subgroup in the low-crosstalk condition also applied this mode of processing in case of bivalent stimuli, despite the raised risk of crosstalk in this latter condition. An extended McNemar's chi-square test revealed a significant difference in the distribution of the used processing modes between both conditions (χ^2 (3, n = 45) = 17, p < .001).

Table 2. Number of participants per subgroup in each crosstalk condition.

	Processors	High-crosstalk Serial	Semi-overlapping	Overlapping	total
Low-crosstalk	Serial	**18**	**-**	**-**	18
	Semi-overlapping	**8**	**6**	**-**	14
	Overlapping	**2**	**7**	**4**	13
Total		28	13	4	45

Impact of Modes of Task-Processing on Performance Measures and Multitasking Efficiency

Switch costs. The mean RT/ER switch costs for the non-preview group and the three subgroups of the preview group in both crosstalk conditions are shown in Table 3 (upper panel). Switch costs based on RT in the low-crosstalk condition were analyzed by a one-way ANOVA, using the group categorization (non-preview, preview-serial, preview-semi-overlapping and preview-overlapping) as between-subject factor. As Levene's test was significant, $F(3,87) = 2.85$, $p = .042$, for the RT switch costs in the low-crosstalk condition, we used a Welch correction for the one-way ANOVA and Tamhane corrected post-hoc pairwise comparisons to account for unequal variances between the subgroups. The Welch corrected one-way ANOVA revealed a significant main effect, $F(3,35.64) = 36.5$, $p < .001$, $n_p = .50$. Whereas the serial processors of the preview group and the participants of the non-preview group exhibited considerable switch costs, the overlapping processors of the preview group were able to reduce these costs to an amount as low as 33.9 ms. The mean switch costs of the semi-overlapping processors were between these extremes. The Tamhane corrected post-hoc comparisons revealed all pairwise differences between the different (sub-)groups as significant (all $p < .004$).

Because of the highly different group sizes, the data of the high-crosstalk condition were analyzed by a Kruskal-Wallis test followed by Bonferroni-Holm corrected Mann-Whitney U test. Again the overall effect ($H(3) = 34.53$, $p < .001$), as well as most pairwise comparisons became significant (all $p < .003$) indicating essentially the same pattern of results as for the low-crosstalk condition. Only the pairwise comparison between the serial subgroup and the non-preview group just failed to become significant ($p = .052$). A closer inspection of the data suggested that the lower RT switch costs in the (semi-) overlapping subgroups were primarily caused by the participants' ability to even generate considerable mean switch benefits, in terms of switch times lower than repetition times, with their fast switches (semi-overlapping subgroup: -124.7 ms in both conditions; overlapping subgroup in low-crosstalk: -116.9 ms, in high-crosstalk: -89.4 ms). Switch costs reflected in ERs were low in both crosstalk conditions (-1.2% to 0.8%) and did not differ significantly from zero in any group (all $p > .11$).

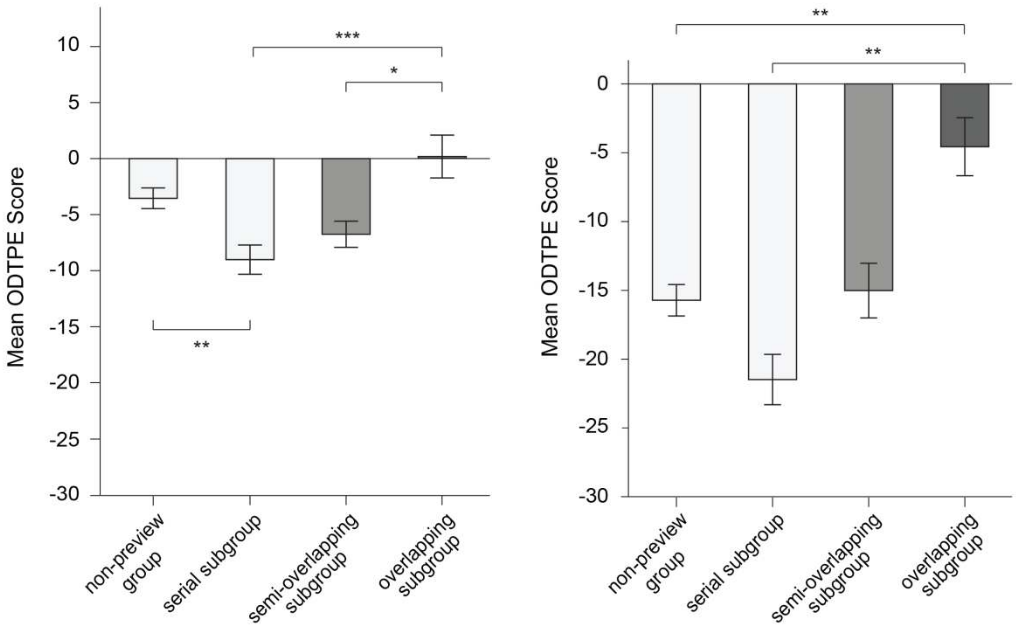
Mixing costs. The mean RT/ER mixing costs for the different (sub-)groups and the two crosstalk conditions are shown in Table 3 (lower panel). Mixing costs in both crosstalk conditions were analyzed for all subgroups separately by one-sample t-tests. None of the mixing costs observed differed significantly from zero (all p > .28). Therefore, we refrained from testing for differences between the subgroups of the preview group and the non-preview group. Moreover, also the mean RT to trials immediately preceding a fast switch was not significantly prolonged compared to the mean single-task RTs for neither of the different (sub-)groups in both conditions (all p > .09). Similarly, also mixing costs reflected in ER were all below zero, actually indicating small mixing benefits.

Table 3. Performance and switch costs by crosstalk condition for the non-preview and preview group: reactions times (RT) in ms, and error rates (ER) in percent.

		Low-crosstalk		**High-crosstalk**	
Costs	**Group**	RT	ER	RT	ER
Switch	Non-preview	195.3	-1.01	380.3	0.04
	Serial	281.1	-0.19	491.1	0.06
	Semi-overlapping	119.5	-0.66	230.5	0.77
	Overlapping	33.9	-0.60	46.1	-1.16
Mixing	Non-preview	-29.6	-0.78	-4.7	-0.62
	Serial	-28.0	-1.14	10.0	-0.34
	Semi-overlapping	-4.2	-1.23	13.0	-1.79
	Overlapping	-18.3	-1.02	8.2	-0.60

Overall Dual-Task Performance Efficiency. The results of the analyses of the overall multitasking efficiency based on the ODTPE measure are shown in Figure 4, separately for the low-crosstalk (left) and high-crosstalk (right) condition. As becomes evident from the figure, a relatively similar picture emerges in the low- and high-crosstalk condition with the overlapping subgroup outperforming the other subgroups and the non-preview group. Remarkably, the overlapping subgroup even achieved an ODTPE value above zero (0.15%) in the low-crosstalk condition. Thus, with a low risk of crosstalk between task stimuli, the overlapping task-processing mode did not result in multitasking costs, but in small multitasking *benefits* compared to single-task performance. These differences in ODTPE scores were confirmed by a one-way ANOVA in the low-crosstalk condition, $F(3,87) = 7.07$, $p < .001$, np = .20, and by a Kruskal-Wallis test in the high-crosstalk condition ($H(3) = 14.51$, $p = .002$). In the low-crosstalk condition, differences were further substantiated by planned Tukey-HSD corrected post-hoc comparisons, which revealed significant differences between the overlapping subgroup and the other two subgroups of the preview condition (all p < .018) and between the serial subgroup and the non-preview group (p = .008; all other: p > .21). In the high-crosstalk condition, Bonferroni-Holm corrected Mann-Whitney U tests indicated that the overlapping subgroup differed significantly from the non-preview group (p = .007) and from the serial subgroup (p = .003). All other differences were not statistically significant (all p > .017).

Fig. 4 Mean overall dual-task performance efficiency (ODTPE) scores for the non-preview group and each preview subgroup in the low (left panel) and the high (right panel) crosstalk condition. Error bars represent ± two standard errors. * p < .05. ** p < .01. *** p < .001. ns = not statistically significant



Task-Processing Mode and Working Memory Capacity (Ospan)

The median split of the distribution of the partial score in the preview group (md = 65) resulted in a subgroup "low working memory capacity" of 23 individuals (*M* = 53, *SD* = 9.5) and a subgroup "high working memory capacity" of 22 individuals (*M* = 71, *SD* = 4.2). A 2 (low vs. high WMC) x 2 (low vs. high crosstalk) repeated measures ANOVA on the rate of fast switches revealed significant main effects of WMC, $F(1,43) = 4.73$, $p = .035$, $\eta_p = .10$, and risk of crosstalk, $F(1,43) = 47.72$, $p < .001$, $\eta_p = .53$, as well as a significant interaction between WMC and risk of crosstalk, $F(1,43) = 7.31$, $p = .01$, $\eta_p = .15$. While in the low-crosstalk condition the mean rate of fast switches was considerably lower in the low WMC subgroup (*M* = 8.8%, *SD* = 3.1%) than in the high WMC subgroup (*M* = 19.6%, *SD* = 3.1%), this difference diminished noticeably in the high-crosstalk condition (low WMC: *M* = 2.2%, *SD* = 1.4%, high WMC: *M* = 4.4%, *SD* = 1.4%).

Discussion

The current research addressed the question to what extent individual preferences for serial versus overlapping processing in the TSWP paradigm are determined by a permanent and rigid predisposition for one of these task-processing modes, or by an individual's strategic choice. For this purpose, we compared performances when switching between two simple classification tasks with either univalent (low risk of crosstalk) or bivalent (high risk of crosstalk) task stimuli under conditions of classical task switching demanding a serial processing of the two tasks versus conditions of TSWP providing options for overlapping processing. However, it was an essential precondition to replicate the finding of previous research (Reissland & Manzey, 2016) that the preview option provided by the TSWP paradigm was actually used for overlapping processing at least by a considerable number of individuals. Therefore, our first set of analyses focused on whether we would already find indications of use of preview in the TSWP conditions, compared to classical task switching, at an overall group level. Such an effect, reflected in reduced or even absent switch costs, was reported at least for conditions with low risk of crosstalk (univalent task stimuli) by Spector and Biedermann (1976) and Reissland and Manzey (2016). Nevertheless, the overall group analysis only revealed a strong effect of risk of crosstalk on switch costs. Replicating an effect well-known from classical task switching studies, which has often been confirmed since then (Allport et al., 1994; Rogers & Monsell, 1995), switch costs were higher in the conditions with the higher risk of crosstalk between tasks. However, no overall benefit of preview was found in either condition. Regarding the preview effect, a little reduction of switch costs was just observed in the low-crosstalk condition, but this effect was too small to become statistically significant at the overall group level.

The obvious reason for the weak preview effect at the overall group level is that, as expected, the participants performing the TSWP paradigm did not represent a homogenous group but included participants who differed in their use of preview. This was revealed by the main set of analyses, including fine-grained analyses of the individually chosen task-processing modes in the two crosstalk conditions. The rationale behind the classification of subgroups exhibiting different modes of task-processing in the preview condition was based on a statistical approach taking a comparison of the distribution of so called fast switches that were detected on a single-trial basis in the preview-group and the non-preview group into account. Along with unchanged RTs for trials preceding a task switch, fast switches were taken as an indicator of overlapping processing. In contrast to Reissland and Manzey (2016), who found a clear dichotomy of serial and overlapping processors, indicated by a discontinuation of the distribution of fast switches in their preview group, the current data does not support a clear-cut classification. Instead a more gradual shift from serial processing towards clear overlapping processing was observed when a task-preview was available. One reason for this difference is the considerable larger sample included in the current research which represents a better basis for analyzing the nature of individual differences. As we aimed for a comparison between participants, who processed unambiguously in either a serial or overlapping manner, we built extreme groups. For this purpose, we defined those individuals as *overlapping processors*, who, based on the comparison of the fast switch rates' distributions, were highly unlikely to belong to the same population as the participants of the non-preview control group, which had to work serially on the tasks. In an analog way, all participants whose number of fast switches did not differ from the distribution found for the non-preview group were considered as distinct *serial processors*. All other participants constituted the remaining *semi-overlapping subgroup*, which exhibited a mix of serial and overlapping processing. This method, based on a strict definition of fast switches and a consideration of possible trade-offs in terms of prolonged response times for trials preceding a fast switch, represents a rather conservative approach to identify overlapping processing, as only incidents are considered where alternative explanations can be excluded. Thus, the rates of fast switches used for classification of the subgroups of semi-overlapping and overlapping processors can be regarded as an estimation of the minimum number of incidents of overlapping processing.

Turning now to the performance consequences of the preferences for serial versus overlapping processing, we first consider the effects arising for the different subgroups in the condition with low risk of crosstalk before we turn to the question to what extent the preferred mode of processing and its efficiency was affected when the risk of crosstalk increased and what individual predispositions could be leading to differences in the preferred mode of processing.

Individual Preferences for Serial or Overlapping Processing Mode in the Low-Crosstalk Condition

The replication of the basic finding of participants, who preferred to process the tasks in a serial manner even when preview was available and others who used the preview for overlapping processing, albeit to a different degree, confirms anecdotal observations reported from one of the earliest task switching studies (Jersild, 1927), and is also in line with similar conclusions derived from research with other multitasking paradigms (e.g., Schumacher et al., 2001, Experiment 3). Inspecting the switch costs for the different subgroups in the condition with preview shows that the participants identified as overlapping processors were able to reduce their mean switch costs to negligible 34 ms. In contrast, the mean switch costs of the semi-overlapping processors were still substantial (120 ms) and those of the serial processors were higher (285 ms) than the mean costs in the non-preview control group (195 ms). Regarding the multitasking efficiency of the three subgroups, it turned out, that the overlapping processors did not only show very small mean switch costs, but were even able to perform slightly more tasks in the given time when working in the mixed condition compared to the single-task blocks. Thus, they did not show any multitasking performance decrements but even a small performance gain. This multitasking gain was mainly due to the fact, that these participants actually realized considerable switch benefits instead of costs with their fast switches. The fact that these benefits did not lead to even higher multitasking gains seems to be related to the fact that even the participants classified as overlapping processors were not able to practice overlapping processing with each switch but only with a certain percentage of switches.

Dependence of Individual Preference for Serial or Overlapping Processing on Risk of Crosstalk Between Tasks

Based on the replication of the individual preferences for different processing modes, the major question of the present study was to what extend individuals would adopt their preferred mode of processing in case of higher risks of crosstalk between tasks? As expected, all participants preferring a serial processing mode in the condition with a comparatively low risk of crosstalk between the tasks used this mode also in the condition with high risk of crosstalk. However, the participants of the other two subgroups showed more flexibility and adapted their mode of processing to the increased risk of crosstalk. Working with bivalent task stimuli involving higher risks of crosstalk (Navon & Miller, 1987) or task confusions (e.g., due to stimulus-response bindings, Logan & Gordon, 2001), the majority of these participants adopted a more serial mode of processing, which allowed for better shielding of the tasks against each other. This shift of task-processing mode provides two important insights. First, it provides evidence that, at least for these two subgroups, the chosen modes of task-processing in multitasking situations are flexible and adaptive with respect to the nature of tasks. This confirms similar conclusions derived from recent PRP research (Fischer et al., 2014; Lehle & Hübner, 2009; Lehle, Steinhauser, & Hübner, 2009; see for a review Fischer & Plessow, 2015). Second, it rules out that benefits of overlapping processing observed with univalent stimuli reflect a (positive) side-effect of an individual's inability to shield the processing threads of the tasks effectively against each other. This had been considered as a possible alternative explanation, based on the assumption that individuals differ in their proneness to effects of visual distractor stimuli (flanker), depending on their attentional capacity (Forster & Lavie, 2007; Lavie & Cox, 1997).

However, there were also participants who did not adopt a more serial mode of processing in case of higher risk of crosstalk. This held true for four participants, who used an overlapping processing mode in both the low- and high-crosstalk condition, and six out of the 14 participants, who showed some indication of overlapping processing, albeit to a limited extent, in both conditions. Inspecting their RTs, resulting switch costs and multitasking efficiency revealed that these participants obviously persisted in their mode of task processing not because they could not do otherwise, but because it was still efficient. Comparing the mean switch costs and multitasking efficiency of the three subgroups in the low- and high-crosstalk condition provided essentially the same pattern of effects for both conditions. Notably, the highest overall multitasking efficiency emerged for the four participants classified as overlapping processors also in the high-crosstalk condition.

The fact that individuals classified as distinct *overlapping* processor outperformed *serial* processors in both crosstalk conditions shows that overlapping processing can efficiently be used to optimize task switching processes, when preview of the stimuli of the task one has to switch to next is available. This is in contrast to findings from PRP research, which suggest that a serial mode of processing represents a more advantageous processing mode in multitasking settings, particularly when there are less degrees of freedom to choose the order of responses (e.g., Logan & Gordon, 2001; Miller et al., 2009). However, whereas the finding from PRP research just accounts for a serial or parallel mode of processing on the central stage of response selection our results regard the efficiency of serial or overlapping processing of whole tasks. This reflects an important difference between the theoretical basis of our research and the dual-task research based on the PRP paradigm. In contrast to the bottleneck model underlying PRP research which assumes that options of overlapping processing provided by processing stages before (i.e. perception) and after (i.e. motor execution) the presumed bottleneck are commonly used by individuals to optimize multitasking performance (Pashler, 1994), the current data show that this holds true only for a subgroup of participants who have a preference for overlapping processing. In contrast, the data of the subgroup of serial processors suggests that they prefer to shield whole tasks entirely, and do not even use possibilities of parallel processing that should be easily available. The fact that such complete shielding of tasks has not been observed in the PRP paradigm might be related to the fact that, in this paradigm, overlapping processing at least of stages before the bottleneck is enforced by presenting the task stimuli in very close succession for a very short period of time only.

The comparison with PRP research and the basic assumptions of the classical bottleneck model also provides some clues what sorts of overlapping processing might have contributed to performance gains of overlapping processors. First, based on the fact that perceptual processes can run in parallel the encoding of the preview-stimulus might have already been completed during the performance of the other task. Second, the overlapping processors might have started top-down processes of task-set reconfiguration (Monsell, 2003) already while still executing the response to the other task. However, the current data are certainly not conclusive in this respect and more research will be needed to clarify this aspect further.

Possible Factors Influencing the Choice of Processing Mode

Another question addressed in the current study concerns how individuals, who voluntarily prefer an (semi-)overlapping mode of processing when risk of between-task crosstalk is low, but flexibly change to a more serial mode of processing in case this risk increases, differ in their preconditions from those principally preferring a serial mode of processing independent of task characteristics. One candidate that we assumed to be relevant in this respect was the WMC. Our data provide significant support for this assumption. Individual differences in WMC, as assessed by the Ospan task (Turner & Engle, 1989), were found to be one determinant of the use of mode of processing. Individuals with a comparatively high WMC were more likely to use the stimulus preview for overlapping processing than individuals with a low WMC. This is in line with other results pointing to a link between WMC and the efficiency of executive function and attentional control (Kane et al., 2007). Even more importantly, WMC interacted significantly with the extent of overlapping processing under different risks of crosstalk. Individuals with comparatively low WMC processed the two tasks always in a serial manner, independent of whether the risk of crosstalk was high or low. In contrast, the majority of participants with comparatively high WMC adapted their mode of processing to the respective risk of crosstalk that is changed from a mode of (semi-)overlapping processing in the condition with low risk of crosstalk to a mode of serial processing, if the crosstalk was high. Out of the four participants who applied an overlapping mode of processing even in the high-crosstalk condition, three belonged to the higher WMC group. Overall, this suggests that WMC is a factor of relevance not only for the preference of a more serial or overlapping mode of processing but also for the capability to adapt these two modes to task characteristics.

Conclusions and Limitation

Overall, the results of the present study provide several new insights which are relevant for our understanding of serial versus overlapping (parallel) processing in multitasking. Especially they suggest that individuals differ concerning a preference for serial and overlapping processing, that these modes of processing can be regarded as poles of a performance dimension describing the degree to what extend individuals make use of overlapping processing when dealing with different tasks, and that the use of overlapping processing can result in performance advantages compared to serial processing even in case of possible risks of crosstalk. Furthermore, at least individuals with high WMC seem to be flexible in adopting their mode of processing to the task context with practicing overlapping processing when risks of crosstalk are comparatively low and task shielding if these risks are high. However, this latter flexibility of adopting the mode of processing to risks of crosstalk between tasks was only shown for a shift from a more overlapping to a more serial mode of processing, if risks of crosstalk between tasks increase, as in the high-crosstalk condition of the present research. A limitation of the present study regards the use of highly similar tasks even in the low-crosstalk condition, as both tasks included visually presented verbal stimuli, which both demanded manual responses. According to the multiple resources model of Wickens (2002) such task similarity hinders instead of supports overlapping processing. Accordingly, this might have contributed to the fact that a considerable percentage of participants preferred to process even the tasks in our low-crosstalk condition in a serial manner. Follow-up research should investigate to what extent these serial processors would keep their mode of processing, if very diverse tasks in terms of their resource demands are used. The TSWP paradigm combined with fine-grained analyses of responses provides a promising tool for such research.

Compliance with Ethical Standards

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Conflict of Interest: Dietrich Manzey declares that he has no conflict of interest. Jovita Bruening declares that she has no conflict of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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Appendix: Definition of Overall Dual-Tasking Performance Efficiency (ODTPE)

The ODTPE measure is a straightforward throughput measure. It describes how many of two tasks can be performed correctly in a given time when an individual has to cope with these two tasks concurrently or in close succession compared to a situation where the same tasks can be performed under single-task conditions[3]. We refer to overall *benefits* of dual-tasking if the overall performance of two tasks performed under dual-task conditions is better, that is more tasks are performed correctly, than what would theoretically be expected in case of strictly separated processing of the two component tasks without considering any dual-tasking costs. *Costs* of dual-tasking are assumed if overall dual-task performance is worse, that is less tasks are performed correctly, than what would be expected from strictly separated processing. This logic can be illustrated by the following *Gedankenexperiment*:

Assume an individual can correctly solve 90 trials of a letter classification task (task A), and 80 trials of a digit classification task (task B), both in a single-task block of *one* minute each. If this individual then has to work on both tasks concurrently and/or in close succession for another *one*-minute block, we would theoretically expect 45 correct responses to the letter classification task and 40 correct responses to the digit classification task, given that (1) this individual works on the two tasks in a strict serial processing mode, (2) this individual is able to perform the different tasks with the same speed as under single-task conditions, and (3) neither general costs or benefits of dual-tasking arise. Considering the performance of the component tasks separately and comparing it to the respective single-task performance, this might suggest a performance decrement of 50% in the dual-task condition. However, considering the overall performance for both component tasks together, and the fact that the time available per task was cut by 50% in the dual-task condition, neither a loss nor a benefit in performance was produced. Thus, the throughput of tasks has actually remained the same for both conditions. Dual-task benefits would be reflected in any higher throughput, that is a total number of correctly performed tasks (summed across both component tasks) higher than 85. This, for example, might be possible if some overlapping processing of the two tasks takes place. In contrast, overall dual-task costs would be reflected in the fact that an individual would achieve a fewer overall number of correct responses than could have been expected from the single-task performance in the single-task blocks (< 85). This could be due to, for example, costs of task switching or costs related to outcome conflicts.

3 Note that we use the term “dual-tasking” for any situation where an individual has to cope with two tasks, including situations of real concurrent performance like in PRP-tasks, situations of classical task switching where individuals have to switch between two tasks, or situations of task switching which provide options of overlapping processing like in our TSWP paradigm.

In our experiments, we worked with single-task blocks of *one* minute and dual-task trials of *two* minutes. If a participant is working strictly serially (without considering any switch and mixing costs) we, thus, would expect the same number of correct responses in single-task and mixed-trials or dual-task blocks, respectively. Following this reasoning, we defined ODTPE formally as follows:

$$ODTPE = 100 * \left[\frac{(nC_{\mathrm{A\_dual}} + nC_{\mathrm{B\_dual}})}{(nC_{\mathrm{A\_single}} + nC_{B\mathrm{\_single}})}\right] - 100$$

With nC_{A_single} and nC_{B_single} defined as number of correct responses in the respective tasks under single-task conditions, and nC_{A_dual} and nC_{B_dual} defined as the corresponding performance in dual-task conditions. Based on this measure, performance benefits of multitasking as described above are reflected in values of ODTPE > 0. In contrast, costs of multitasking are reflected in values of ODTPE < 0. Note that the consideration of the number of correct responses generates an overall efficiency measure that represents costs and benefits reflected in both, response times and error rates.