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Are processing limitations of visual attention and response selection subject to the same bottleneck in dual-tasks?

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Abstract Visual attention and response selection are processes that are limited by capacity. The present study focuses on whether visual attention is subject to the response selection bottleneck. This was investigated by conducting 2 dual-task experiments of the psychological refractory period (PRP) type. A visual conjunction search task was chosen as Task 2 in these experiments. Conjunction search requires the binding of the stimulus' defining features. This binding is performed in a serial search process in displays of different amounts of stimuli until the presence or absence of the target is correctly indicated. In Experiment 1, the conjunction search was combined with a 2-choice tone discrimination Task 1, and in Experiment 2 with a 2-choice color discrimination Task 1. Detailed reaction time (RT) analyses revealed concurrent performance of visual search to both tone and color in Task 1's response selection. In conclusion, visual attention is not subject to the response selection bottleneck.

Keywords Dual-task procedures (PRP) · Visual search · Psychological refractory period

Psychological studies have provided evidence for the existence of different types of capacity limited processes in the cognitive system. For example, visual attention processes during visual search tasks (Treisman & Gelade, 1980) and the response selection in dual-task situations are potentially capacity limited (Pashler, 1994; Welford, 1952; but see Meyer & Kieras, 1997). While the capacity limitation in visual search tasks usually leads to increasing search times depending on number and type of the stimuli, a processing bottleneck induces a sequential processing of response selection processes in two tasks of a dual-task situation (see below for details). However, until today, the capacity limitations of visual attention and the bottleneck mechanism in dual-tasks have mostly been studied separately in different research areas. Considering the multitasking situations we have in our complex human world, it is important to explore the interplay between visual attention and attention for response selection from a real-world as well as from a theoretical perspective. In the current study, we investigate whether visual attention is subject to the same bottleneck mechanism as response selection in dual-task situations. First, we report findings concerning the capacity limitation of focal visual attention, then we explain the bottleneck processing in dual-task situations, and at the end we focus on their combined investigation before specifying the main approach of the current study.

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Capacity limitation in visual attention

Researchers proposed the paradigm of visual search in order to investigate the basic mechanisms of visual attention. In a typical visual search paradigm, the visual search display consists either of a target surrounded by distractors or exclusively of distractors and is briefly presented to the participants who are asked to determine whether the target is present or absent. Treisman and Gelade (1980) proposed two different types of visual search paradigms in their feature integration theory (FIT). The target differs from the distractors in a single feature (e.g., a red target among green distractors) in *feature search*, whereas the target differs in a combination of two features from the surrounding distractors (e.g., a red vertical target among red horizontal and green vertical distractors) in *conjunction search*. In feature search, the target is found quickly since it pops out by differing in a unique feature from the distractors. The pop-out is realized by preattentive processes that extract features like color, orientation, and luminance and that operate fast and parallel across the whole visual field. These preattentive processes presumably consume no attentional capacity. Consequently, manipulating the number of items in the search display – the set size – usually does not lead to increasing search times. Conjunction search, on the other hand, requires a binding of the target-defining features (e.g., color and orientation). According to Treisman and Gelade (1980), focal attention is necessary to bind the extracted features, and this focal attention operates serially. The shifting of focal attention over the conjunction search display until the target is detected is due to the capacity limitation in visual attention. An experimental finding that underlines this mechanism is the observation of increasing search times with larger set sizes (see also Treisman, 1982, 1998; Logan, 2004; Müller & Krummenacher, 2006; Nakayama & Silverman, 1986; but see Sung, 2008).

Furthermore, the serial deployment of visual attention is reflected in the ratio of performance in target absent compared to target present trials. In target absent trials, the binding of the target features has to be performed theoretically for all items in the search array. The search can be terminated before searching all items after the target is detected in target present arrays. Therefore, the reaction time (RT) is usually longer because the exhaustive target absent search needs more time compared to the self-terminating target present search (Wolfe et al., 1990; Wolfe, 1998a).

The assumption of a strict dichotomy of preattentive feature search and visual attention–based conjunction search, initially proposed by Treisman and Gelade (1980), has been discussed critically (see also Treisman, 1988, and Treisman & Sato, 1990, about alternative assumptions). Duncan and Humphreys (1989, 1992; Humphreys, Hodsoll, Olivers, & Yoon, 2006) could show that the perceptual discrimination between target and distractors influences visual search performance. In particular, they found pop-out effects (i.e., shallow search slopes across different set sizes) in a visual search task requiring the conjunction of two features. In this case, the difference in saliency between target and distractors was sufficient to find the target efficiently. Alternatively, Wolfe, Cave, and Franzel (1989) and Wolfe (1994, 2007) developed the guided search model, which proposes a search process that is based on a combination of parallel and serial search mechanisms to find the target in the search display. Among others, this combination of search mechanisms is determined by target information that guides visual attention deployment.

Although the debate on these various models is important for the literature of visual attention, the present study will not offer a solution to this debate. Rather, the aim of the present study is to examine whether the limitation in visual attention has the same origin as the processing bottleneck inducing response selection in dual-task situations to be performed one after another. Therefore, the current study focuses on the classic conjunction search task following FIT (Treisman & Gelade, 1980). Visual attention is required for binding the stimulus' defining features. The serial manner in which the binding is performed in this conjunction search task reflects the limitation in visual attention deployment. We implement the classical conjunction search task (Treisman & Gelade, 1980) in a dual-task setting because it is an open issue whether the limitation in visual attention inducing that serial manner of attention allocation according to FIT is subject to the same bottleneck mechanism as the response selection in dual-task situations.

The response selection bottleneck

Another type of processing limitation is revealed in dual-task situations in which two tasks have to be processed simultaneously. The paradigm of the psychological refractory period (PRP) type (Pashler, 1994; Welford, 1952) is a well-known dual-task paradigm in which two choice RT tasks are presented with varying temporal interval (stimulus onset asynchrony; SOA), and participants are instructed to prioritize the performance of the task that is presented first. Typically, the RT of Task 2 (i.e., RT2) increases with decreasing SOA while the SOA manipulation usually does not affect the RT of Task 1 (i.e., RT1).

Many researchers assume that a central bottleneck exists at the response selection stage in choice RT tasks (Pashler, 1994; Schubert, 1999, 2008; Welford, 1952). According to the central bottleneck model, mental operations like response selection are processed sequentially across tasks because the central mechanism only allows the processing of one task at a time. The processing stages of Task 2 that require the response selection mechanism can only start after the corresponding stages of Task 1 have left the bottleneck. RT2 can thus be decomposed in the waiting time for the bottleneck, the slack time, and the proper task execution time (i.e., perception, response selection, and motor stages). The assumption of a capacity limitation at the central bottleneck can thus explain increasing RT2 with decreasing SOA; the shorter the SOA, the longer the response selection stage in Task 2 must wait for the end of the response selection stage in Task 1. In the current study, we will investigate whether the capacity limitation inducing serial processing in visual conjunction search tasks is subject to the central bottleneck in dual-task situations of the PRP type.

Previous work on interference between visual attention and response selection

Pashler (1989) constructed a hybrid paradigm combining aspects of a PRP task and an accuracy-based Task 2. The second task was presented at short and long SOA after an auditory first task requiring the discrimination between a low and a high tone. Task 2 was an accuracy-based task in which the search display was masked. There were eight search letters consisting of green *O*s and red *T*s; in target present trials, one of the items was replaced randomly by a green T. The items were presented briefly and then masked by *X*s until the response was given. Pashler asked participants to respond as fast as possible to the tones in Task 1 and to give an unspeeded response to the presence or absence of the search target in Task 2, thereby focusing on accuracy in this visual search task. As a result, the accuracy levels were similar for high and low temporal overlaps between both tasks (i.e., at short and long SOA). Pashler concluded that tone discrimination and visual search can be concurrently processed and that the visual search processes are not subject to the central capacity limitation of the response selection.

De Jong and Sweet (1994) proposed a different assumption. They adapted the tasks of Pashler (1989) in a modified experimental situation. They tested the effects of different preparatory task instructions on the latencies of the tone discrimination in Task 1 and on the accuracy of Task 2 in a task situation similar to Pashler's (1989). The participants had to indicate the highest digit in the display in Task 2 (a number between 6 and 9). Numbers from 1 up to the highest digit displayed minus 1 served as distractors. The visual stimulus presentation was masked. The authors could show that the identification of the highest digit in the second task suffered from the prioritized preparation of the first task at high but not at low temporal overlap – in this experiment, SOAs of 50 and 1,000 ms. The finding showed that the temporal overlap can have an influence on the accuracy in Task 2 that is unlike the results of Pashler. De Jong and Sweet succeeded in explaining the apparent discrepancy to Pashler's findings with the results of another experiment. In that experiment, the authors used Pashler's SOA variation of 50, 150, and 650 ms. The authors found reduced visual identification accuracy in Task 2 at short compared to long SOA. However, the performance difference between the shortest and the longest SOA was not as large as in the previous experiment. A comparison across both experiments confirmed that the difference in accuracy for the digit Task 2 was larger between the SOAs 50 and 1,000 ms compared to the SOAs 50 and 650 ms. Since accuracy in Task 2 was higher at SOA 1,000 compared to SOA 650 ms, De Jong and Sweet (1994) concluded that frequently the SOA 650 ms could have provided insufficient time to complete Task 1 (note, however, that the mean RT for Task 1 was faster than 650 ms) and – importantly – to switch preparation to Task 2 before the display was masked. Thus, if the SOA was long enough, visual attention and response selection were less likely to interfere, whereas a short SOA reduced accuracy in Task 2, showing mutual dependencies on the same capacity limitation.

Conclusions on dual-task processing in the context of PRP situations rely on RT analyses because RT delays are suited to detect constraints in concurrent processing that are less likely to be revealed in accuracy. The previously described studies focused exclusively on accuracy data. Pashler (1991), however, used another experimental design in which he disentangled the dependency between RT and accuracy data in dual-tasks consisting of both speeded and accuracy tasks. Visual attention had to be shifted to a probe in Task 2 of the dual-task situation in the main experimental condition. The probe was a short horizontal line that marked the target letter in a letter display. The task was to identify the target letter. In most of the experiments (Pashler, 1991), the display was masked after a short duration. Task 1 required the speeded discrimination between two tones. While Pashler found no dependency between the accuracy in Task 2 and the speed in Task 1 in these experiments, he found a PRP effect in the RT data in Task 2 in experiments in which Task 2 required a speeded response to nonmasked stimuli. Although these findings agree with the assumption that visual attention shifts in Task 2 are not subject to response selection processes in Task 1, the data cannot exclude that the visual attention shift was postponed after the response selection of Task 1 (Pashler, 1991).[1]

Overall, the described experiments offer a first approach in order to determine to what extent visual attention and response selection performance interfere in a dual-task situation. The study of De Jong and Sweet (1994) complemented the experiments of Pashler (1989) by indicating that an adequate choice of SOA has to be considered when examining dependencies between attention for response selection and visual attention deployment in a dual-task situation. Still, there are two reasons why the findings do not offer a satisfying answer to the question whether visual attention is subject to the same bottleneck mechanism as the response selection in dual-task situations (see Treisman & Gelade, 1980). First, masking the search display (as in the studies of Pashler, 1989, and De Jong & Sweet, 1994) typically shortens the processing time and the visual persistence of the stimuli, both in case of a direct search for the target and in case of an attentional shift towards the probe indicating the

[1] Note that in Experiment 4, Pashler (1991) analyzed the RT2 data on the visual attention task in two experimental conditions; in Condition (1) the probe was presented simultaneously with the letter display and in Condition (2) it was presented 100 ms before the letter display, thus allowing a prior attention allocation to the relevant target position of the letter. Pashler reported an underadditive interaction (see Fig. 1, Panel B) between the probe presentation manipulation and the SOA on the RT2 data, which on first glance and according to the locus-of-slack logic might look as evidence for the assumption that the visual attention shifts in Task 2 had been executed during the slack time of Task 2. However, as Pashler (1991) pointed out, the findings do not really exclude an alternative model according to which the pure attention shift had been postponed after the response selection in the two conditions at short SOA and that at long SOA the prior probe presentation had caused a decrease of RT2 in Condition (2) compared to Condition (1).

target (Pashler, 1991). The encoded perceptual information is likely to decay and would not be available for further processing (see also Jolicoeur & Dell'Acqua, 1999). In other words, the mask may stop certain visual attention processes, like searching around the items to find the target. Therefore, there is an important difference between visual attention deployment when the target is masked and when it is not masked. That is why the present study does not mask the search display so that visual attention can be deployed serially.

Second, the described studies lack a systematic manipulation of the amount of visual attention needed in Task 2. This systematic manipulation is essential when investigating specific predictions of processing at the same or different bottlenecks in the context of the locus-of-slack method (Pashler & Johnston, 1989; and see below). Therefore, we will vary the number of search items, the set size, systematically in Task 2. We will also insert speeded choice RT tasks since accuracy and RT measures differ in the scope of information they present (Kantowitz, 1978; Meyer, Yantis, Osman, & Smith, 1985). RT measures enable us to conduct a specific RT analysis of the performance in various search conditions in Task 2 when combined with a variable set size. This allows us to address the current research question that will be outlined next.

The locus-of-slack method

We applied the locus-of-slack method (Schweickert, 1978, 1980) to investigate whether visual attention is subject to the same bottleneck mechanism as the response selection in dual-task situations. According to the locus-of-slack method, it is possible to infer whether a targeted processing stage in Task 2 and response selection in Task 1 are carried out sequentially or concurrently by investigating the impact of a difficulty manipulation of that processing stage and SOA on RT2 in a PRP task (see below). As can be seen in Fig. 1, Panel A depicts a model of sequential processing and Panel B depicts a model of concurrent processing. The locus-of-slack method is used to reveal which of the models applies for the respective task situation.

Several authors have reported successful applications of the locus-of-slack method to test for sequential or concurrent processing stages in a dual-task. McCann and Johnston (1992), for example, used a dual-task study in which the SOA between two tasks and the difficulty of the response selection stage in Task 2 were manipulated. In Task 2, the mapping of stimulus to response information was either easy or hard (i.e., compatible vs. incompatible). Importantly, RT2 was longer for the same amount of time for the hard compared to the easy mapping, irrespective of the SOA manipulation between both tasks. Thus, SOA and response selection difficulty affected RT2 *additively* (see Fig. 1, Panel A). According to McCann and Johnston, this additive pattern of SOA and the difficulty effects emerges because sequential processing of response selection in Task 1 and Task 2 induces a slack time before response selection in Task 2. The hard response selection in Task 2 results in longer RT2 both at short and long SOA compared to the easy one since the additional amount of time emerges after the slack time (see also De Jong, 1993; Johnston & McCann, 2006; Pashler, 1984; Pashler & Johnston, 1989; Schubert, 1999, 2008).

If the targeted process in Task 2 is performed concurrently with the response selection in Task 1, we will expect another pattern of findings. In that case, one should expect an *underadditive* interaction of SOA and the difficulty manipulation of visual search Task 2 on RT2. As we will explain below in detail, in case of an underadditive interaction, visual search processes can be deployed during the slack time of the response selection bottleneck. Consequently, the duration of these processes is absorbed into the slack time and not added to the overall RT2 at short SOA. However, at long SOA, there is no slack time during which visual search could be performed, and the duration of the search processes is fully added to the overall RT2. Hein and Schubert (2004) and several others reported that RT2 pattern. They used an auditory two-choice discrimination task as Task 1 and presented a visual task as Task 2 that required a two-choice letter classification. The difficulty of the visual task was manipulated by presenting the letters either in high or low contrast against a background so that they were easy or hard to classify. It has to be noted that the amount of RT2 slowing in the hard compared to the easy task condition was reduced at short compared to long SOA. Therefore, the manipulated factors SOA and perceptual difficulty in Task 2 yielded underadditive effects on RT2 (see Fig. 1, Panel B). According to the locus-of-slack method, the underadditive SOA and difficulty interaction arises because the manipulated stage is located before the response selection in Task 2. Therefore, the extra amount of time needed for the difficult Task 2 condition can be absorbed into the slack time and will not be added to the overall RT2 at short SOA. There is no slack time at long SOA, and the effect of the difficult Task 2 condition is fully added to RT2 (see also Pashler & Johnston, 1989). Other characteristic examples for studies reporting underadditive SOA by perceptual difficulty effects were reported (e.g., De Jong, 1993; Johnston, McCann, & Remington, 1995; Schubert, Fischer, & Stelzel, 2008).

Overall, the locus-of-slack method relies on difficulty manipulations of the targeted processes in Task 2 and SOA (see Fig. 1): While additive effects indicate sequential processing (Panel A), an underadditive difficulty and SOA interaction is consistent with concurrent processing of the targeted process and response selection in Task 1 (Panel B). The first option is in line with the assumption that visual attention is subject to the same bottleneck mechanism as response selection in dual-task situations. The second option, however, coincides with the assumption that visual attention is not subject to the same bottleneck mechanism as response selection in dual-task situations.

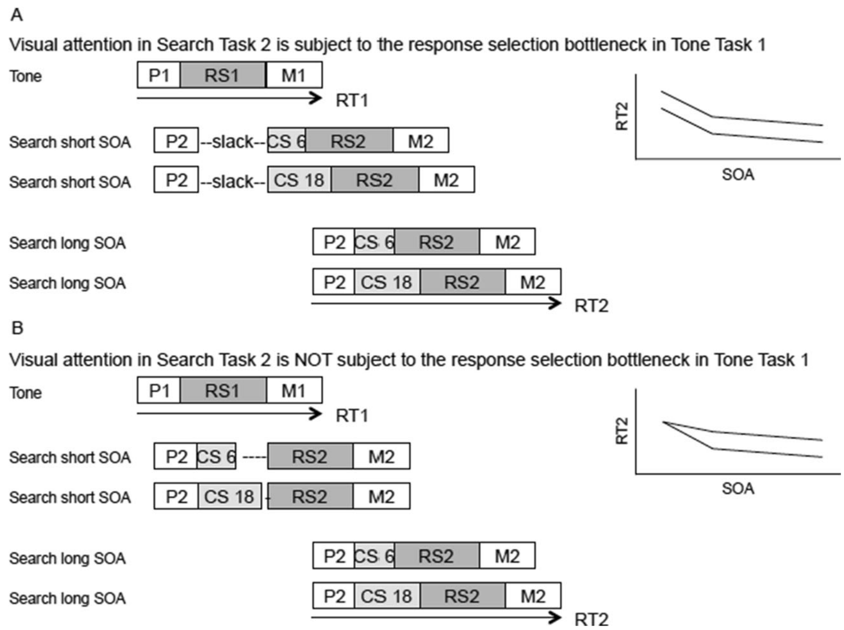

Fig. 1 Panel A: Additive effects of stimulus onset asynchrony (SOA) and conjunction search processes on reaction times (RTs) should result when processing stages at or beyond the response selection bottleneck are affected. The response selection bottleneck induces sequential performance of the response selection stages of two tasks. Exemplary, the manipulation in the visual search Task 2 is illustrated by different set sizes. Panel B: Underadditive interactions of SOA and conjunction search processes on RTs should result when processing stages before the response selection bottleneck are affected. Exemplary, the manipulation in the visual search Task 2 is illustrated by different set sizes. P1 = perception stage of Task 1; RS1 = response selection stage of Task 1; M1 = motor stage of Task 1; P2 = perception stage of Task 2; CS 6/CS 18 = conjunction search set size 6/18; RS2 = response selection stage of Task 2; M2 = motor stage of Task 2; RT1 = reaction time to the tone; RT2 = reaction time to the search

Rationale of the present study

We applied the locus-of-slack method in the present study to investigate whether visual attention is subject to the same bottleneck mechanism as response selection in dual-task situations. A visual conjunction search Task 2 in combination with a two-choice discrimination Task 1 was therefore presented in a PRP dual-task situation, and RTs were assessed. A two-choice tone discrimination Task 1 was administered in Experiment 1. This cross-modal dual-task setting is similar to the previous settings in Pashler (1989) as well as De Jong and Sweet (1994), who also used cross-modal dual-tasks with an auditory Task 1 and a visual Task 2. Experiment 2 consists of a two-choice visual color discrimination Task 1 and a visual search Task 2. This enables us to investigate whether visual attention can proceed concurrently with another task in a dual-task situation in which both tasks draw on the visual modality.

Two hypotheses shown in Fig. 1 were tested. Visual attention deployment was varied by indicating the presence or absence of the target in search arrays of different set sizes. The difficulty of the search process was varied by presenting 6, 12, or 18 items (Treisman & Gelade, 1980). The SOA between Task 1 and conjunction search Task 2 was also varied. If the manipulated factors (i.e., set size, target present vs. absent) influence a processing stage of the visual search Task 2 that is at or beyond the response selection bottleneck, the manipulation should result in an equal prolongation of Task 2, both at short and long SOA. The corresponding RT2 pattern would indicate that visual attention is deployed after the response selection in Task 1 has finished. The resulting additive effects of SOA and Task 2 difficulty manipulation would be consistent with the assumption of a common capacity limitation underlying visual attention and response selection leading to sequential performance (but see also Meyer & Kieras, 1997). If the manipulation of the visual search Task 2 affects a processing stage that is not subject to the response selection bottleneck, however, the conjunction search processes should yield a different RT2 pattern at short compared to long SOA. At short SOA, the longer search time for increasing set sizes, and the absence of the target should be absorbed into the slack time of Task 2 and not added to the overall RT2. At long SOA, there is no slack time, and the time needed for the manipulated processing stages of the conjunction search Task 2 should fully propagate into RT2. This should result in an underadditive interaction of SOA and Task 2 manipulation on RT2, reflecting that visual attention and response selection are not subject to the same bottleneck but are processed concurrently.

Experiment 1

The dual-task experiment consists of a two-choice tone discrimination Task 1 and a conjunction search Task 2 that are presented with variable temporal overlap (i.e., SOA). Both tasks require speeded reactions. We conducted a detailed RT analysis to assess whether visual attention is subject to the same bottleneck mechanism as response selection in dual-task situations.

Methods

Participants Twenty-four participants (eight male) from the Ludwig-Maximilians-Universität München and the Humboldt-Universität zu Berlin, with a mean age of 24.8 years (*SD* = 3.1 years, age range 20–34 years) took part in Experiment 1. We chose this particular sample size as 24 participants had been tested in other studies in which the locus-of-slack method was also applied (see, for example, Janczyk, Augst, & Kunde, 2014; Jentzsch, Leuthold, & Ulrich, 2007; Johnston, McCann, & Remington, 1995).[2] All participants were right-handed and had normal or corrected-to-normal vision. They were not aware of the purpose of the study and were paid at a rate of 8 € per hour for their participation.

Apparatus and stimuli The experiment was conducted on a computer[3] using Presentation (Version 14.8 12.30.10). The search display was shown on a 17-in. CRT monitor at a resolution of 1,024 × 768 pixels in the conjunction search task, with a refreshing rate of 100 Hz. The display area was a square measuring 17.5° on a side with a viewing distance of 60 cm. Each stimulus had a size of 4.1° × 1.2° in the visual search display. The stimuli were presented in red (CIE: × = 0.640, y = 0.329; luminance = 19.3 cd/m^2), and green (CIE: × = 0.300, y = 0.600; luminance = 55.4 cd/m^2) against a black (CIE: × = 0.313, y = 0.329; luminance = 0.2 cd/ m^2) background. Three display sizes of 6, 12, and 18 items were used to manipulate the feature binding processes in conjunction search. In the target absent condition, half of the items were green vertical and the others were red horizontal bars. When a target was present, one of the red bars was presented in a vertical position; that is, an extra target item was not added to keep similar set sizes in target present and absent trials. Participants responded to target absent trials by pressing the "," key and to target present trials by pressing the "." key using the index and middle fingers of their right hand on a QWERTZ keyboard, respectively.

Two sine-wave tones of 350 Hz (78 dB) and 900 Hz (80 dB) had to be discriminated in the auditory stimulus discrimination task. They were presented via headphones and were played equally often in every block. Participants were asked to press the "Y" key for the 350 Hz tone and the "X" key for the 900 Hz tone using the middle and index fingers of their left hand, respectively.

Trial sequence The trial sequence for the dual-task is shown in Fig. 2. Each trial started with the presentation of a fixation cross at the center of the screen for 500 ms. The auditory stimulus was then displayed for 100 ms. The presentation of the first stimulus was also the starting point for the SOAs 50, 100, 350, or 800 ms, after which the search display appeared. The search display was shown until the participant's response. The maximum presentation duration was 2,500 ms. Error feedback was given when the response to the first stimulus, to the search display or to both tasks was incorrect or omitted. The feedback consisted of the word FALSCH (incorrect) that was shown at the center of the screen for 500 ms. The intertrial interval (ITI) was 1,000 ms.

[2] One can also determine the number of required participants by conducting an a priori analysis of power as had been proposed by the G*Power program of Faul, Erdfelder, Lang, and Buchner (2007). Note that the 4 (SOA) × 3 (set size) interaction is most important for the present research, and therefore it would be wishful to provide the required sample size that is necessary to assess the validity of the statistical test of that interaction. However, to our knowledge, G*Power can be used only for research designs with repeated measurements in which an interaction is tested for two within-subject factors and in which at least one of the two factors has no more than two levels (Faul et al., 2007). Because of that limitation, we calculated the required sample size (as an a priori power analysis procedure) for the situation of a 4 (SOA) × 2 (set size) interaction with G*Power (Rasch, Friese, Hofmann, & Naumann, 2010). In our view, this is justified because many studies using the locus-of-slack technique use only two levels for the manipulated processing stage in a PRP task and compare a difficult version of the targeted process with an easy version of the targeted process depending on SOA. For the current situation we calculated the power for the situation with the two set size conditions, that is, if a condition with a set size 18 is compared to a condition with a set size 6 (not regarding the medium condition 12) depending on SOA (four levels). This in particular are the two extreme set size conditions in the current investigation and we reasoned that if we had a sufficient number of participants ensuring sufficient power for that 4 × 2 interaction, this would be a good approximation for the required number of participants in the 4 × 3 interaction.

For G*Power, we specified the following parameters (Faul et al., 2007; Rasch et al., 2010): Test family: *F* tests; Statistical test: ANOVA: Repeated measures, within factors; Type of power analysis: a priori; Effect size f': 0.3536 (because f' = sqrt(p) * f = sqrt(2) * 0.25 = 0.3536 where 2 corresponds to the two levels of the factor set size and 0.25 is the effect size f recommended by G*Power); α err prob: .05; Power (1 - β err prob): .80; Number of groups: 1; Number of measurements: 4; Corr. among rep measures: 0.5; Nonsphericity correction ε: 1. The calculated sample size amounts to 13. Considering that this approximate power analysis probably underestimates the power of the most relevant 4 (SOA) × 3 (set size) interaction, we believe that the current sample size of 24 participants (which was informed by related studies in literature) is large enough to guarantee sufficient power for testing the interaction of interest. This holds for Experiments 1 and 2.

[3] The computer was a no-name PC Intel Core 2 CPU 4300 1.8 GHz, 1 GB RAM, 150 GB HDD; the video card was a VIA/S3G Uni Chrome Pro IGP; the operating system was Windows XP Professional SP3. The monitor was a Sony Trinitron E250, 1,024 × 768 pixels, 100 Hz, True Color (32 bit).

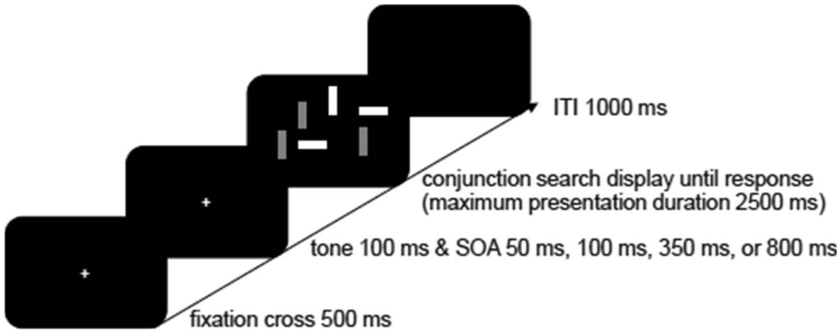

Fig. 2 Trial sequence for Experiment, 1 consisting of a two-choice tone discrimination Task 1 and a conjunction search Task 2. Here, the search condition target present set size 6 is displayed; originally there were one red vertical, two red horizontal, and three green vertical bars. ms: millisecond; SOA: stimulus onset asynchrony; ITI: intertrial interval

Design and procedure A three-factor within-subject design with SOA, set size, and display type as independent variables was used. There were 48 trials per block resulting from each combination of 4 SOAs (50, 100, 350, 800 ms) × 3 set sizes (6, 12, 18) × 2 display types (target present, target absent) × 2 auditory stimuli (350, 900 Hz).

The procedure was as follows. The experiment started with single-task practice of both the auditory stimulus discrimination (48 trials) and the search task (144 trials) followed by dual-task practice (48 trials). Then, 576 PRP dual-task trials were presented in 12 blocks of 48 trials each. In the dual-task blocks, participants were instructed to respond as fast and accurately as possible to both tasks with priority on Task 1. The participants started each block by pressing the space bar and were asked to take short breaks between the blocks. The experimental session lasted about 60 minutes in total.

Results

The RT of Task 2 and Task 1 were analyzed separately with repeated measures analysis of variance (ANOVA; Type III sum of squares) with the three factors SOA, set size, and display type. *P* values were adjusted using the Greenhouse-Geisser correction when assumptions of sphericity were violated. Error trials included incorrectly committed and omitted responses. Trials with errors in one or both tasks were excluded in the RT analyses. The error rates of Task 2 and Task 1 were arc-sine transformed (Kirk, 2013) and submitted to the same statistical analyses as RT.

Task 2 RT RT2 data is displayed in Fig. 3A and B. We found a PRP effect for the conjunction search Task 2, $F(3, 69) = 115.118$, $MSE = 45{,}476.91$, $p < .001$, $\eta_p^2 = .83$. RT2 increased significantly from long SOA (mean, $M = 699$ ms) to short SOA ($M = 971$ ms), which is consistent with the assumption of a bottleneck interrupting the processing chain of Task 2. As expected for conjunction search performance, there was a main effect of set size, $F(2, 46) = 70.422$, $MSE = 3{,}868.66$, $p < .001$, $\eta_p^2 = .75$, and a main effect of display type, $F(1, 23) = 4.410$, $MSE = 9{,}113.34$, $p < .05$, $\eta_p^2 = .16$. As can be seen in Fig. 3A, RT2 was longer for set size 18 ($M = 883$ ms) than for set size 12 ($M = 834$ ms) and set size 6 ($M = 809$ ms) as well as for target absent ($M = 851$ ms) compared to target present ($M = 834$ ms).

Most important for the current research question was that SOA and set size affected RT2 underadditively, $F(6, 138) = 2.692$, $MSE = 6{,}500.59$, $p < .05$, $\eta_p^2 = .11$. The conjunction search Task 2 and the bottleneck processes of Task 1 were performed concurrently. A planned comparison revealed that the RT2 difference between set size 18 and 6 at short SOA 50 was significantly smaller than the corresponding difference at long SOA 800, $t(23) = 2.781$, $p < .05$. This finding coincided with the assumption that the additional search time for the large set size compared to the small set size was indeed absorbed into the slack time and that the visual search processes were not subject to the bottleneck. In particular, absorption of RT2 of set sizes 18 and 6 left mean RT2 differences of 38 ms at short compared to 99 ms at long SOA. Furthermore, the SOA and display type interaction proved to be significant as well, $F(3, 69) = 5.962$, $MSE = 3{,}210.02$, $p < .01$, $\eta_p^2 = .21$. Thus, the decision whether the target was absent or present was performed during the slack time. A planned comparison revealed that the RT2 difference between target absent and target present trials at short SOA 50 ($M = 17$ ms) was significantly smaller than the corresponding difference at long SOA 800 ($M = 23$ ms), $t(23) = 2.761$, $p < .05$. This finding was also in line with the assumption that the additional search time for target absent compared to target present was absorbed into the slack time. Overall, the visual search processes in Task 2 were not subject to the response selection bottleneck in Task 1.[4]

Task 2 search slopes Additionally, we analyzed the search slopes across all three set sizes for the conjunction search Task 2 shown in Table 1. The search slopes express the rate at which the items are processed. We ran a linear regression

[4] Please see the appendix for a discussion on an alternate explanation of the results.

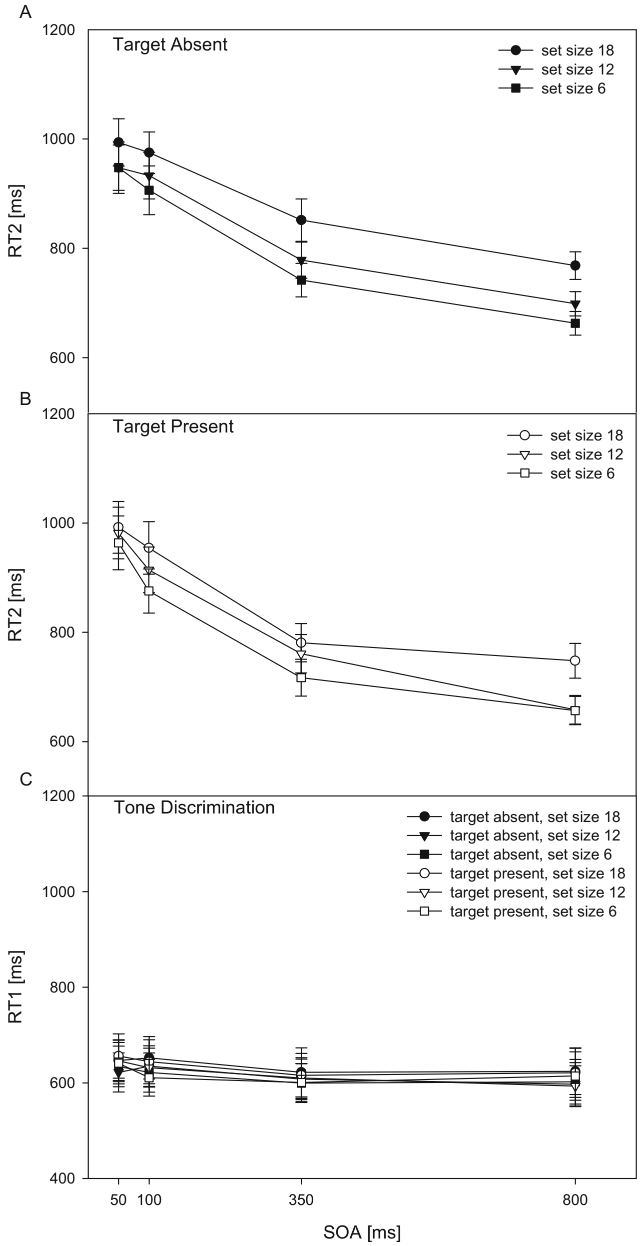

Fig. 3 Experiment 1: Reaction times of the tone discrimination (RT1) and the conjunction search (RT2) depending on stimulus onset asynchrony (SOA) and set size (6, 12, & 18). Panel A: Illustration of RT2 for target absent trials. Panel B: Illustration of RT2 for target present trials. Panel C: The graph shows RT1 when target absent and target present trials were performed in Task 2. Error bars represent standard error of the mean.

across all three set sizes to calculate the search slopes for each SOA and target presence vs. target absence, respectively. The analysis revealed an SOA effect on the search slopes. The mean search slopes decreased with decreasing SOA from 8.2 ms/item (SOA 800) to 3.2 ms/item (SOA 50), $F(3, 69) = 3.911$, $MSE = 87.33$, $p < .05$, $\eta_p^2 = .15$. Search performance was more efficient at short compared to long SOA. This observation is consistent with the assumption that the additional search time for the larger set size is absorbed into the slack time at short SOA. Therefore, there is less influence of the search time per item on RT2 at short compared to long SOA. No other effects reached significance.

Table 1 The table shows mean search slopes (ms/item) across all three set sizes for the conjunction search Task 2 combined with a tone discrimination Task 1 in Experiment 1 and a color discrimination Task 1 in Experiment 2 as a function of SOA and Task 2 manipulation (display type).

	SOA (ms)							
	Experiment 1				Experiment 2			
Display type	50	100	350	800	50	100	350	800
Absent	3.9	5.7	9.1	8.8	6.4	9.8	9.1	10.2
Present	2.4	6.6	5.3	7.6	2.4	5.1	2.5	8.3

Note. SOA: stimulus onset asynchrony; ms: millisecond

Task 1 RT RT1 are displayed in Fig. 3C. RT1 decreased slightly from short SOA 50 ($M = 642$ ms) to long SOA 800 ($M = 609$ ms), as was revealed by an effect of SOA on RT1, $F(3, 69) = 3.351$, $MSE = 21{,}212.79$, $p = .054$, $\eta_p^2 = .13$. The observed RT1 slowing coincides with the observation of Tombu and Jolicoeur (2002). They showed that an RT1 slowing may occur at short SOA under difficult Task 2 conditions. The conjunction search Task 2 could be a difficult task as it requires high demands of visual attention. Besides, Task 1 processing was slightly affected by the set size manipulation of Task 2, $F(2, 46) = 4.826$, $MSE = 4{,}642.37$, $p < .05$, $\eta_p^2 = .17$. RT1 was slowed down for 20 ms when set size 18 ($M = 636$ ms) followed the tone discrimination task compared to set size 6 ($M = 616$ ms).

Task 2 and Task 1 error rates analysis An overview of the mean error rates in percent for both tasks is provided in Table 2. The data of Task 2 demonstrated a main effect of set size, $F(2, 46) = 6.392$, $MSE = .06$, $p < .01$, $\eta_p^2 = .22$. The participants made more errors when the set size was large compared to small (set size 18 vs. set size 6: $M = 9.3$ % vs. 7.0 %). Fewer errors were made when the target was absent ($M = 5.4$ %) compared to present ($M = 9.7$ %), $F(1, 23) = 54.830$, $MSE = .09$, $p < .001$, $\eta_p^2 = .70$. The set size and display type interaction was significant, $F(2, 46) = 8.941$, $MSE = .08$, $p < .001$, $\eta_p^2 = .28$, indicating fewer errors in target absent compared to target present trials when the set size was small compared to large (target absent, set size 6 vs. 18: $M = 6.1$ % vs. 5.2 %; target present, set size 6 vs. 18: $M = 7.9$ % vs. 13.3 %). The interaction of SOA and set size was also significant, $F(6, 138) = 3.759$, $MSE = .06$, $p < .05$, $\eta_p^2 = .14$, which indicates that participants made more errors with increasing set size at long SOA 800 (set size 6 vs. set size

Table 2 The table shows mean error percentages for the conjunction search Task 2 combined with a tone discrimination Task 1 in Experiment 1 as a function of SOA and Task 2 manipulation (set size, display type).

		Experiment 1				
		SOA (ms)				
Task	Set size	Display type	50	100	350	800
2	6	Absent	5.7	8.5	5.6	4.7
		Present	8.5	10.6	6.6	5.9
	12	Absent	5.2	5.0	6.1	3.6
		Present	9.2	9.2	7.8	5.4
	18	Absent	6.1	4.3	5.9	4.5
		Present	12.5	13.0	9.5	18.2
1	6	Absent	3.7	4.7	2.1	1.2
		Present	3.4	3.4	2.1	1.2
	12	Absent	3.4	4.7	1.9	1.9
		Present	3.1	4.0	1.7	0.9
	18	Absent	3.7	3.1	1.6	1.4
		Present	4.5	1.7	2.6	1.7

Note. SOA: stimulus onset asynchrony; ms: millisecond.

18: $M = 5.3$ % vs. 11.4 %) compared to short SOA 50 (set size 6 vs. set size 18: $M = 7.1$ % vs. 9.3 %).

In Task 1, participants made more errors at short SOA ($M = 3.6$ %) compared to long SOA ($M = 1.4$ %), $F(3, 69) = 13.745$, $MSE = .06$, $p < .001$, $\eta_p^2 = .37$. The remaining main effects and interactions were not significant.

Discussion

Tone discrimination and conjunction search were performed as Task 1 and Task 2 in Experiment 1, respectively. In particular, RT2 yielded underadditive effects of the conjunction search conditions and the temporal overlap variation (i.e., SOA) between both tasks. The binding of the stimulus defining features in the search Task 2 was performed during the slack time before the bottleneck processing in Task 2. These findings derived from detailed RT analysis following the locus-of-slack method thus extend results of earlier studies (De Jong & Sweet, 1994; Pashler, 1989). Altogether, the present experiment provides evidence for the assumption that limitations in visual attention are not subject to bottleneck processes of Task 1.

Experiment 2

The findings of Experiment 1 suggest that the deployment of visual attention in a conjunction search Task 2 is not subject to the response selection bottleneck occurring from the simultaneous processing of an auditory discrimination Task 1. Nevertheless, it might be that the current task situation, which is characterized by stimuli of different modalities (i.e., auditory and visual) could have facilitated the concurrent processing of conjunction search and the auditory Task 1. According to Wickens's multiple resource model (2008; see also Wickens & Liu, 1988) that assumes independent resources on different dimensions (e.g., input modalities, codes of processing, and stages of processing), different input modalities rely on different attentional capacities enabling concurrent processing. On the other hand, if two tasks require stimulus processing in the same modality, then interference is expected between the two tasks at the input stages because these stages rely on the same attentional capacity and this should restrict concurrent processing (Magen & Cohen, 2010). Experiment 2 addresses the question of whether the finding in Experiment 1 can be generalized to a dual-task situation with stimuli of the same input modality.

We presented a color discrimination Task 1 together with the conjunction search Task 2 that was used in Experiment 1 for that purpose. Both tasks require the same visual information processing modules according to a modality specific interference model (see Magen & Cohen, 2010; Wickens, 2008;). If under those conditions the conjunction search Task 2 cannot proceed concurrently anymore with the response selection process of the visual Task 1, we should find additive effects between SOA and the set size manipulation on RT2. However, if the concurrent deployment of both visual attention and response selection in the visual Task 1 is a general phenomenon, which does not depend on the processing modalities between the two tasks, then we should observe an underadditive interaction of SOA and set size on RT2 again.

Methods

Twenty-four new participants (seven male) from the Humboldt-Universität zu Berlin with a mean age of 25.1 years ($SD = 3.1$ years, age range 20 –30 years) took part in Experiment 2. We tested 24 participants again as the power analysis of Experiment 1 had shown that this sample size was sufficient to reveal the interactions that are in the focus of the present study. Experiment 2 was identical to Experiment 1 with the following exceptions: a two-choice color discrimination Task 1 preceded the conjunction search Task 2 in which two triangles, colored blue (CIE: × = 0.199, $y = 0.238$; luminance = 34.2 cd/m^2) and yellow (CIE: × = 0.419, $y = 0.505$; luminance = 77.9 cd/m^2), had to be discriminated. Each equilateral triangle had a point on the top and subtended 2.5° × 2.5°. The stimuli were shown equally often in a counterbalanced order with the Task 2 conditions. One triangle per trial was presented at the center of the screen. Note that the conjunction search stimuli never appeared at this location. Participants responded to the yellow triangle by pressing the "Y" key and to the blue triangle by pressing the "X" key using their middle and index fingers of their left hand.

Results

The data handling for the statistical analysis was similar to Experiment 1.

Task 2 RT RT2 is shown in Fig. 4A and B. We found a significant main effect of SOA indicating the basic PRP effect, $F(3, 69) = 109.032$, $MSE = 42{,}759.89$, $p < .001$, $\eta_p^2 = .83$, mirrored by increasing RT2 with decreasing SOA (SOA 50 vs. SOA 800: $M = 921$ ms vs. 646 ms). As expected for conjunction search, we observed two main effects of set size and of display type, $F(2, 46) = 66.151$, $MSE = 6{,}490.31$, $p < .001$, $\eta_p^2 = .74$, and $F(1, 23) = 11.091$, $MSE = 20{,}877.64$, $p < .01$, $\eta_p^2 = .33$, respectively. Participants responded slower with increasing set size (set size 6 vs. 12 vs. 18: $M = 740$ ms vs. 772 ms vs. 820 ms) and for target absent ($M = 797$ ms) compared to target present ($M = 757$ ms). The factors set size and display type interacted significantly as well, $F(2, 46) = 5.341$, $MSE = 9{,}126.33$, $p < .05$, $\eta_p^2 = .19$, indicating slower responses with increasing set size for target absent (set size 6 vs. 18: $M = 749$ ms vs. 855 ms) compared to target present (set size 6 vs. 18: $M = 730$ ms vs. 785 ms).

Most important – as in Experiment 1 – we found a significant underadditive SOA and set size interaction, $F(6, 138) = 4.944$, $MSE = 3{,}227.83$, $p < .001$, $\eta_p^2 = .18$, indicating that the conjunction search Task 2 and the bottleneck processes in Task 1 were performed concurrently. A planned comparison revealed that the RT2 difference between set sizes 18 and 6 was significantly smaller at short SOA 50 ($M = 53$ ms) than at long SOA 800 ($M = 111$ ms), $t(23) = 4.726$, $p < .01$. The additional processing time of the more demanding conjunction search set size 18 compared to set size 6 was absorbed into the slack time at short SOA. Additionally, the interaction of SOA and display type was significant, $F(3, 69) = 8.283$, $MSE = 4{,}883.24$, $p < .001$, $\eta_p^2 = .27$, further indicating that the conjunction search Task 2 was performed concurrently with the bottleneck processes of Task 1. A planned comparison of the RT2 differences of target absent and target present between short ($M = 3$ ms) and long SOA ($M = 68$ ms) was significant, $t(23) = 4.121$, $p < .01$. Thus, additional processing time in target absent (i.e., more attention demanding than target present) was absorbed into the slack time at short SOA. Altogether, the observed pattern of underadditive interactions of SOA and set size just as of SOA and display type on RT2 showed that visual attention operates concurrently with the bottleneck processing in Task 1, even when both tasks require visual processing.

Moreover, we found a significant interaction of SOA, set size, and display type on RT2, $F(6, 138) = 2.578$, $MSE = 2099.21$, $p < .05$, $\eta_p^2 = .10$, which was probably due to slight differences between the SOA and set size interaction patterns in target present and target absent. As can be seen in Fig. 4A and B, the absorption of the conjunction search processing into the slack time was complete for target present, while it was incomplete for target absent. This was reflected by a significant underadditive interaction of SOA and set size for target present, $F(6, 138) = 5.665$, $MSE = 2284.36$, $p < .01$, $\eta_p^2 = .20$, but a nonsignificant interaction for target absent, $F(6,$

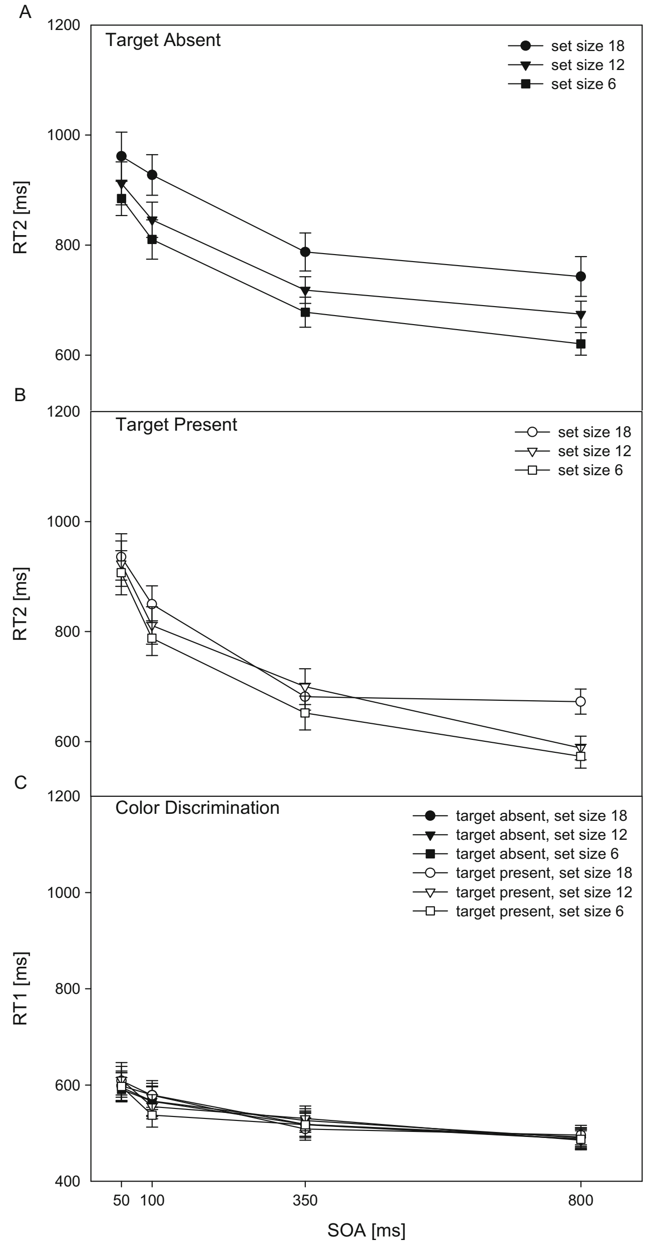

Fig. 4 Experiment 2: Reaction times of the color discrimination (RT1) and the conjunction search (RT2) depending on stimulus onset asynchrony (SOA) and set size (6, 12, & 18). Panel A: Illustration of RT2 for target absent trials. Panel B: Illustration of RT2 for target present trials. Panel C: The graph shows RT1 when target absent and target present trials were performed in Task 2. Error bars represent standard error of the mean.

138) = 1.500, MSE = 1,920.09, p = .183, η_p^2 = .06. Considering target present in more detail, a planned comparison strengthened the finding that visual search Task 2 was performed completely concurrently with the bottleneck processes of Task 1. The comparison of the RT2 difference between set sizes 18 and 6 across short (M = 29 ms) and long SOA (M = 100 ms) was significant, $t(23)$ = 3.473, p < .01. For target present, the processing time of the more demanding conjunction search set size 18 compared to set size 6 was fully absorbed into the slack time at short SOA, even when Task 1 required visual processing. Thus, altogether, the current observations of the underadditive SOA and set size as well as the underadditive SOA and display type interactions are consistent with the assumption that absorption of conjunction search processing in the slack time of Task 2 has occurred for both target present and target absent, but with different degree as revealed by the SOA, set size, and display type interaction.

Task 2 search slopes The search slope analysis of conjunction search Task 2 when Task 1 was a two-choice color discrimination task is shown in Table 1. We calculated the search slopes as in Experiment 1. Statistical analysis revealed decreasing mean search slopes with decreasing SOA from 9.3 ms/item (SOA 800) to 4.4 ms/item (SOA 50), $F(3, 69)$ = 7.306, MSE = 28.83, p < .01, η_p^2 = .24. The visual search Task 2 was performed more efficiently at short compared to long SOA. As in Experiment 1, this finding is consistent with the assumption that visual search performance has been absorbed into the slack time for the larger set size at short SOA, leading to less variability at short compared to long SOA. Additionally, we found a main effect of display type, $F(1, 23)$ = 6.243, MSE = 142.83, p < .05, η_p^2 = .21. Slopes were steeper for target absent (M = 8.9 ms/item) compared to target present (M = 4.6 ms/item) indicating higher visual attention demands for target absent compared to target present.

Task 1 RT Figure 4C displays RT1 of color discrimination Task 1 that showed a main effect of SOA, $F(3, 69)$ = 25.147, MSE = 30,141.30, p < .001, η_p^2 = .52. Participants responded slower at short SOA 50 (M = 601 ms) compared to long SOA 800 (M = 490 ms), which was similar to Experiment 1. We also found a main effect of set size, $F(2, 46)$ = 4.229, MSE = 1,158.72, p < .05, η_p^2 = .16, revealing that Task 1 processing was slightly affected by the set size manipulation in Task 2 (set size 18 vs. set size 6: M = 548 ms vs. 538 ms). All other effects and interactions did not reach significance.

Task 2 and Task 1 error rates analysis As illustrated in Table 3, the statistical analysis of the conjunction search Task 2 yielded more errors for increasing set size (set size 6: M = 4.6 % vs. set size 18: M = 5.5 %), $F(2, 46)$ = 5.190, MSE = .03, p < .01, η_p^2 = .18. Furthermore, participants made more errors when the target was present (M = 5.9 %) compared to absent (M = 3.4 %), $F(1, 23)$ = 23.585, MSE = .10, p < .001, η_p^2 = .51. Both factors interacted significantly, $F(2, 46)$ = 8.776, MSE = .07, p < .001, η_p^2 = .28, reflecting an increased error rate for target present but a decreased error rate for target absent with increasing set size (target present, set size 6 vs. 18: M = 4.8 % vs. 8.0 %; target absent, set size 6 vs. 18: M = 4.4 % vs. 3.0 %). The error rate analysis for the color discrimination Task 1 revealed a significant influence of SOA, $F(3, 69)$ = 4.702, MSE = .07, p < .01, η_p^2 = .17. Participants committed more errors at short (M = 3.1 %) compared to long SOA (M = 1.7 %). In addition to the more elevated error rate at short compared to long SOA, the difference in the error rates between target absent and target present was larger for the small set size (SOA 50 vs. SOA 800: M = 1.4 % vs. 1.1 %) compared to the large set size (SOA 50 vs. SOA 800: M = 0.3 % vs. 0.1 %). This finding was indicated by the significant interaction of SOA, set size and display type on the error rate in Task 2, $F(6, 138)$ = 2.317, MSE = .04, p < .05, η_p^2 = .09. No other effects or interactions reached significance.

Table 3 The table shows mean error percentages for the conjunction search Task 2 combined with a color discrimination Task 1 in Experiment 2 as a function of SOA and Task 2 manipulation (set size, display type).

			Experiment 2			
			SOA (ms)			
Task	Set size	Display type	50	100	350	800
2	6	Absent	5.4	5.6	3.3	3.1
		Present	6.4	5.9	2.8	4.0
	12	Absent	3.0	2.6	2.4	4.0
		Present	6.6	3.6	5.9	3.6
	18	Absent	2.8	3.3	2.6	3.1
		Present	9.5	8.2	5.9	8.2
1	6	Absent	3.5	3.0	2.6	1.4
		Present	2.1	2.1	1.2	2.3
	12	Absent	3.0	3.5	1.6	2.3
		Present	3.5	1.6	2.6	1.0
	18	Absent	3.5	2.1	2.3	1.7
		Present	3.2	2.3	2.1	1.6

Note. SOA: stimulus onset asynchrony; ms: millisecond

Discussion

Experiment 2 investigated whether or not the observation in Experiment 1 – that the visual attention processes in a conjunction search Task 2 and the bottleneck processing in Task 1 operate concurrently – is restricted to tasks with different stimulus modalities. Clearly, the results showed that attention demanding binding processes in the conjunction search can be deployed concurrently with response selection when a visual discrimination task is simultaneously processed. Thus, the findings of Experiment 2 extend the results of Experiment 1 (two-choice tone discrimination and conjunction search) by revealing concurrent performance of conjunction search to response selection even when both Task 1 and Task 2 require visual information processing.

General discussion

Research objectives

In the present study, we investigated whether visual attention is subject to the same bottleneck mechanism as the response selection in dual-task situations. Detailed RT analysis following the locus-of-slack method (see McCann & Johnston, 1992; Pashler & Johnston, 1989) was applied to test if visual attention demanding conjunction search was subject to the response selection bottleneck in a two-choice RT dual-task setting. In Experiment 1, a tone discrimination Task 1 preceded visual search. The RT analysis revealed a concurrent performance of visual search Task 2 to bottleneck processes in Task 1. In Experiment 2, the general pattern of results could be replicated for a dual-task situation of a visual discrimination Task 1 and a conjunction search Task 2. However, concurrent processing was not as complete as in Experiment 1.

Visual attention and bottleneck processing in dual-task contexts

Pashler (1989) could show that accuracy was not impaired at short SOA in the visual search Task 2 in a previous study. Based on this observation, he concluded that processes of visual search were not subject to the bottleneck processes of the auditory Task 1. The findings of the present study are consistent with Pashler's results insofar as both feature binding and the decision concerning the presence or absence of the target were not subject to the bottleneck processes of Task 1, either.

The present results of Experiment 1 extend the earlier findings and offer a more coherent understanding of visual attention processing. Contrary to the present experiments, a mask was used in Pashler's (1989) study (just as in De Jong & Sweet, 1994) that may have led to termination of visual attention deployment after its presentation and which may have obscured a possible interference between the task processing. Also, as proposed by De Jong and Sweet (1994), a proper test of whether accuracy in Task 2 is affected by the performance in Task 1 requires a sufficiently long interval between the short and long SOAs, (i.e., Task 1 should have been finished before Task 2 is presented at long SOA). In our study, unmasked visual stimuli ensured visual attention deployment without any constraints. Additionally, the set size variation was the appropriate manipulation to study the limitation in visual attention deployment reflected by increasing RT2 with increasing set size. We analyzed RT2 following the locus-of-slack technique to examine the proper functioning of the visual attention mechanism (i.e., feature binding) for the different search conditions. The locus-of-slack technique helped us to disentangle the amount of visual attention that was processed during the slack time. We showed that visual attention can be performed for different conditions (i.e., set size, display type) during the slack time and that it is not subject to bottleneck processes of Task 1. Our study therefore extends the findings of Johnston et al. (1995), who also applied the locus-of-slack method. Whereas they focused on stimulus identification processes in the second task, we tested a specific visual attention process, the binding of two features, and manipulated this process in different conditions (i.e., set size, display type).

Experiment 2 was conducted to examine whether the observation of Experiment 1 (concurrent processing of visual attention in Task 2 and response selection in Task 1) also applies for two tasks with visual input modalities. According to a modality specific interference account (Wickens, 2008; see also Magen & Cohen, 2010), one might have assumed that the visual attention process in conjunction search Task 2 could be subject to the bottleneck in Task 1 if visual attention was also required in Task 1. However, the locus-of-slack analysis revealed again that visual search was carried out concurrently with the bottleneck processes of Task 1. The perceived underadditive SOA and set size interaction pointed to independent processes that do not share the same dimension in the context of Wickens' multiple resource model. Hence, the main results of Experiment 2 were similar to the findings of Experiment 1: Visual attention processes were neither subject to the bottleneck of an auditory Task 1 (Experiment 1) nor of a visual Task 1 (Experiment 2).

Full and partial absorption of visual search time into the slack time

Nevertheless, a closer look at the data of Experiment 2 revealed slight differences in the amount of slack time processing between target present and target absent. The search time of target present was fully absorbed into the slack time, as shown by the significant interaction of SOA and set size. On the other hand, visual search processing was partially subject to bottleneck processes in target absent trials, especially in set size 18 (see also Fig. 4A and B). Note that post hoc contrasts at short SOA for target absent showed full absorption only when comparing set sizes 6 and 12 ($p > .05$) but not when comparing set size 18 and the other set sizes ($ps < .05$). It has to be noted that there are hints for a similar absorption pattern in Experiment 1, although the corresponding interaction between SOA, set size, and display type was not significant.

Nevertheless, visual inspection shows an RT2 pattern in Experiment 1, which is roughly similar to that in Experiment 2 (compare Fig. 3A vs. 4A and Fig. 3B vs. 4B). Additional separate post hoc contrasts at short SOA showed a difference between RT2 for set size 18 compared to set size 12 as well as for set size 18 compared to set size 6 (ps < .05). The findings indicate that the visual search time for set size 18 was not fully absorbed into the slack time when the target was absent. Analogous comparisons between set sizes 6, 12, and 18 for target present were nonsignificant (ps > .05).

It is important to consider the differences in visual attention deployment to explain this apparent discrepancy between the results for target absent and target present. When the target is present, search processes are operating until the target is found and then terminate, whereas when the target is absent, search processes are theoretically operating until all the items of the display have been attended to. This usually leads to faster RTs for target present compared to target absent and, probably, to less visual attention demands for target present than target absent (Treisman & Gelade, 1980; Wolfe, Palmer, & Horowitz, 2010). Consequently, in both experiments, the complete target present and a large part of the target absent search were processed during the slack time, whereas a small part of the target absent search – set size 18 – was processed after the slack time. Generally, the visual attention process could operate during the slack time. However, for set size 18 in Experiment 2 (just as partially in Experiment 1), especially the target absent demands exceeded the available slack time and, as a consequence, a small part of the search process was postponed after the bottleneck at short SOA. However, in our view this partial postponement does not reflect the operation of an immutable bottleneck between visual attention and response selection since the corresponding SOA and set size interaction was significant. Instead, it reflects the partial postponement of search processes across a small number of items in set size 18, which cannot take place anymore in the restricted slack time.

The locus-of-slack method has been used by many research groups to examine whether a process in Task 2 is subject to the response selection bottleneck. An overview can be found here.[5] The collected RT graphs show full absorption at short SOA for various studies (i.e., Pashler & Johnston, 1989; Maquestiaux, Hartley, & Bertsch, 2004; Tombu & Jolicoeur, 2005; Jentzsch, Leuthold, and Ulrich, 2007. Our RT2 graphs of set sizes 6 and 12 for both target present and target absent coincide with these examples. As discussed above, the attentional demands in target absent set size 18 exclusively exceeded the slack time leading to partial absorption. To further explain this discrepancy, it has to be noted that we tested the hypothesis of concurrent processing of visual attention and response selection by increasing the set size for the relevant process in Task 2 without changing the physical appearance of the stimuli, whereas other research groups mostly changed the physical appearance of the to be processed stimuli in Task 2 without changing the number of the stimuli (i.e., Jentzsch et al., 2007; Maquestiaux, Hartley, & Bertsch, 2004; Pashler & Johnston, 1989; Tombu & Jolicoeur, 2005). It should be considered that changing the number of the to be processed stimuli could be more demanding than changing their physical appearance, which, in turn prevents full absorption in extreme conditions.

Concepts on visual search and implications for research on dual-tasks

There is an ongoing debate in the literature of conceptualizing visual search performance to infer the underlying mechanisms of visual attention deployment. The efficiency of the processes in a visual search task has been the focus of interest in the last years, whereas the terms *parallel search* and *serial search* turned out to be too simplistic to compare the findings of numerous visual search tasks consistently. Typically, the efficiency is reflected in the size of the search slopes that express the rate at which items are processed. Wolfe (1998b) proposed a continuum of search slopes for search tasks with a target present condition as a guideline. Correspondingly, the search slope for the target present condition of the conjunction search task that was used in the present study should be around ~ 5–10 ms/item. According to Wolfe, visual search resulting in such a slope is labeled “quite efficient” compared to “efficient” (~0 ms/item; feature search), “inefficient” (~20–30 ms/item; i.e., spatial configuration search), and “very inefficient” (~ >30 ms/item; i.e., conjunction search of two orientations). Since Wolfe’s data were based on single-task performance but our search task was part of a dual-task situation, the search slopes of SOA 800 represent the most appropriate data that is comparable to the search slope continuum. Note that at SOA 800, Task 2 is usually processed after Task 1, and this resembles a single-task condition. The slope analyses for Experiment 1 and 2, shown in Table 1, revealed that the search slopes at SOA 800 were in the range of ~ 5–10 ms/item (Experiment 1 and 2, M = 8.2 ms/item and 9.3 ms/item). Conclusively, we could show that a visual search task requiring the conjunction of two features yields quite efficient search slopes and is not subject to bottleneck processes of another task.

It should be noted that we focused primarily on the conceptualization of visual search performance in the current study as proposed by FIT (Treisman & Gelade, 1980). We are aware of other debates (Duncan & Humphreys, 1989; Eckstein, 1998; Eckstein, Thomas, Palmer, & Shimozaki, 2000; McElree & Carrasco, 1999; Wolfe, 1994, 2007) that will offer new research questions in the future. For example, whether the findings of the present study also apply for a

[5] An overview of studies using the locus-of-slack method is provided at: http://laplab.ucsd.edu/PRP_Replic.pdf

visual search task requiring more visual attention demands than the present conjunction search task in turn producing "inefficient" or even "very inefficient" slopes (Wolfe, 1998b) should be examined. A spatial configuration search task yields such slopes, as it requires aspects of mental rotation – for example, searching for a rotated *T* among rotated *L*s (Thornton & Gilden, 2007), or a digital 2 among digital 5s (Wolfe et al., 2010). Such a spatial configuration search task could be inserted as Task 2 in a dual-task situation to test whether its processes are subject to the response selection bottleneck, to enlarge the theoretical understanding of limited visual attention deployment.

Relation to electrophysiological studies

The current results also relate to recent studies that used EEG/ERP (electroencephalography/event-related potential) measures to examine the processing characteristics of visual attention in dual-task situations (e.g., Brisson & Jolicoeur, 2007a, b; Lien, Croswaite, & Ruthruff, 2011). For example, Lien et al. (2011) investigated whether visual attention (in Task 2) could be deployed concurrently with both an auditory two-choice Task 1 (i.e., high vs. low tone) and a visual two-choice Task 1 (i.e., number magnitude task) in different experiments. Task 2 consisted always of an unspeeded visual search task in which the identity of a masked target letter had to be indicated via button press. The authors assessed the effect of the SOA manipulation on the N2pc, a marker of covert allocation of visuospatial attention to the lateralized search target (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999, 2003). The N2pc amplitude presumably indexes the amount of allocated visuospatial attention and its latency should reflect the efficiency of the attention shift (see also Töllner, Strobach, Schubert, & Müller, 2012). The results of Lien et al. (2011) showed that the N2pc amplitude was not attenuated at short SOA with respect to long SOA. Furthermore, there was no SOA effect on the N2pc onset latencies. Based on these findings, the authors concluded that irrespective of a two-choice Task 1 requiring the processing of auditory or visual stimuli, the deployment of visuospatial attention was not affected by response selection of Task 1. These conclusions were consistent with the results of the present study. However, they result from qualitatively different experimental designs. Lien et al. used a masked visual search Task 2 combined with a nonspeeded response. In that way, the deployment of visual attention was artificially restricted and visual information decayed – similar to Pashler's study (1989). Also, the task resembled more a memory than a serial visual attention-based search. The demands in visual attention deployment differed as well between their and our studies. Lien et al. used a constant set size of 4 items (see also Brisson & Jolicoeur, 2007a, b), whereas we used three set sizes of 6, 12, and 18 items. The current search task clearly required a larger amount of visual attention, and therefore our findings allow us to generalize the conclusion for feature binding processes needed in larger set sizes.

An interesting fact is that Lien et al. (2011) also tested the effect of an auditory and a visual four-choice discrimination Task 1 on the potential subjection of the visual search Task 2 to the bottleneck. The authors found that the N2pc amplitude was attenuated at shorter SOA compared to longer SOA under these conditions. They concluded that due to the increased response selection demands in Task 1, visual attention processing was delayed after the bottleneck in Task 2. This finding was similar to EEG/ERP studies of Brisson and Jolicoeur (2007a, b). Comparing their studies to our study, one has to consider that EEG/ERP and RT measurement provide different information about task processing. The authors concluded that the reduced N2pc amplitude at short compared to long SOA showed that visual attention deployment in Task 2 interfered with the processing in Task 1. According to the authors, the amplitude of the N2pc is an indicator of the efficient deployment of visual attention to the lateralized search target. The reduced amplitude should reflect a less efficient deployment of visual attention in Task 2. Although the amplitude was reduced at short compared to long SOA, the authors did not discuss the possibility that the less efficient deployment of visual attention could still have been sufficient to solve the visual search Task 2 concurrently with the bottleneck processes. The amplitude analysis did not answer this question nor did it provide information concerning another possibility that Task 2 might have been only partially processed after Task 1. On the other hand, our study design and the locus-of-slack analysis provided conclusive evidence of these questions. We could demonstrate that visual attention was mostly processed during the slack time by comparing RT2 of different visual search conditions between short and long SOAs. Only for an extreme case, our analysis indicated that visual attention deployment exceeded the slack time and was partially processed after the bottleneck (i.e., Experiment 2, target absent set size 18).

Conclusion

The present study investigated whether visual attention is subject to response selection bottleneck processes in Task 1 of two dual-task situations, respectively. In Experiment 1, the conjunction search Task 2 followed an auditory two-choice discrimination Task 1 and in Experiment 2, it followed a visual two-choice discrimination Task 1. For both experiments, detailed RT2 analysis revealed that visual attention and response selection were performed concurrently. However, in case the demands of the visual search task increased the slack time (i.e., Experiment 2, target absent set size 18), the search was delayed after the bottleneck. Whether the visual attention deployment benefitted from an easy response selection of

Task 1 during the slack time is an open question for future research, considering that EEG/ERP findings provided evidence for a delay of the visual attention deployment when response selection demands of Task 1 increased (Brisson & Jolicoeur, 2007a, b; Lien et al., 2011). Overall, the experiments of the present study emphasize that visual attention can be deployed concurrently with bottleneck processes, hence allowing for fast interactions within the complex human world.

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Appendix

One of the reviewers noticed that there might be an alternative explanation for the results of Experiment 1 (as well as of Experiment 2). According to that, response selection in Task 1 and visual attention deployment in Task 2 might not occur simultaneously, but response selection in Task 1 could be so quick that it would complete before visual search could start in Task 2. In that case, a later, motor bottleneck could have caused the underadditivity between set size and SOA on RT2 data, given that both tasks required manual responses.

Although it was not the main aim of the current study to specify the particular bottleneck location but to test whether or not visual attention is subject to a bottleneck, we agree that there might be different assumptions about which bottleneck is responsible for the observed data pattern. In our view, a test of the alternative assumption is difficult though not impossible. As will be seen there are some findings, which suggest that the proposed alternative seems not to be a very likely candidate assumption explaining the complex pattern of findings in the current experiment. In what follows, we outline two implications of the proposed alternative, which can be tested with the current data.

The first implication (1) is related to the part of the alternative explanation, that Task 1 response selection could be completed quickly enough that it would not overlap with visual search processes in Task 2. Consequently, a response selection bottleneck would not be likely to arise. However, if the response selection bottleneck was less likely to arise, the slack time would not be likely to arise either so that the visual search time in Task 2 could not be absorbed into it at short SOA. Whereas this implication would be relevant for very fast Task 1, the situation looks quite different for the case of slow Task 1 processing. In that case, the response selection bottleneck would be likely to arise and the arising slack time would allow for absorption of visual search time into slack again. Consequently, the speed of Task 1 would influence the amount of absorption of visual search Task 2 into the slack time of the response selection bottleneck. This is implication (1) of the alternative assumption, which can be tested by analyzing the amount of the absorption of visual search time at short SOA depending on the speed of Task 1 processing. We will outline the corresponding findings below.

Now to implication (2) of the alternative assumption (i.e., that a motor bottleneck has occurred and is responsible for the absorption). Theoretically, a motor bottleneck would lead to sequential processing of the motor responses in Task 1 and Task 2 in addition to the response selection bottleneck (De Jong, 1993) or instead of a response selection bottleneck. Although the evidence of a motor bottleneck has been critically discussed in the literature (see controversial findings, e.g., of Karlin & Kestenbaum, 1968; Keele, 1973; Meyer & Kieras, 1994, 1997; Bratzke, Rolke, & Ulrich, 2009 and other authors, e.g. Schubert, 1999; van Selst & Jolicoeur, 1997; Sommer, Leuthold, & Schubert, 2001), we will discuss the possibility that a motor bottleneck may explain the observed pattern of visual search time absorption.

First of all, for reasons of completeness, we would like to mention that, theoretically, it could be assumed that a bottleneck could have occurred at the response selection stage and at the motor stage. Although the evidence for such a double bottleneck model is rather rare in literature (but see De Jong, 1993), the model would make the same predictions as the response selection model, which is followed in the present study, and not obscure the findings. Since visual attention would still be processed during the slack time of the response selection bottleneck, the end of the response selection in Task 2 would be the same in all search conditions. Therefore, the waiting time for the motor bottleneck would be similar in all search conditions so that the overall RT2 would be affected by the same amount of time. Even if a motor bottleneck would additionally interrupt the processing stream at the motor stages, there would be no difference in the overall RT2 between set sizes 18 and 6 at short SOA so that SOA and set size would interact underadditively. Therefore, the idea of a double-bottleneck model does not change the current interpretation of the data.

Now to the idea that a motor bottleneck is responsible for the current absorption of visual search time into slack of an emerging motor bottleneck alone. As already outlined evidence for such a model is rare in literature for the current type of dual-task situations and it is difficult to test with the current data set. However, one idea to decide with the current data set, whether a motor bottleneck might have occurred or not, is to calculate the IRI (interresponse interval) data and to test the amount of absorption into slack depending on IRI. The logic behind this analysis is that the probability of a motor bottleneck to occur should be larger under conditions of short IRI because here the motor responses in the two tasks are scheduled closer in time compared to the situation with long IRI. Accordingly, a slack time because of a motor bottleneck should occur rather only under condition of short IRI but not under conditions of a large IRI (see De Jong, 1993). Therefore, in order to test implication (2) of the alternative assumption, i.e. that a motor bottleneck might have occurred and might have been responsible for absorption, could be tested by analyzing the amount of absorption of visual search time into the slack time depending on the IRI.

Next we describe the empirical data as they relate to a test of implication (1) and of implication (2). Concerning implication (1), we tested whether the speed of Task 1 would influence the amount of absorption of visual search Task 2 into the slack time of a bottleneck in the current task situation. Accordingly, we conducted a distribution analysis in which we compared the amount of absorption of visual search Task 2 (the RT2 difference between set sizes 18 and 6) between the trials with fast and with slow RT1 at short SOA. For that purpose, we calculated the RT1 quartiles for each participant and conducted a repeated measures ANOVA on the RT2 differences between set sizes 18 and 6 with the factor RT1 quartile. In Experiment 1, the factor RT1 quartile was not significant, $F(3, 69) = 1.348$, MSE = 12500.75, $p = .27$, $\eta_p^2 = .06$, (RT2 corresponding to the RT1 quartiles: M = 52 ms, 61 ms, 1 ms, 42 ms). In Experiment 2, the factor RT1 quartile was not significant either, $F(3,69) = 2.522$, MSE = 43.264, $p = .10.$, $\eta_p^2 = .099$, (RT2 corresponding to the RT1 quartiles: M = 71 ms, 63 ms, 62 ms, 15 ms). In both experiments, the amount of absorption of visual search Task 2 did not depend on the processing time of Task 1. This is not consistent with the assumption that Task 1 could have been processed so fast that it would have been completed before visual search Task 2 could have started. Rather, the findings indicated that Task 1 and Task 2 overlapped in both slow and fast Task 1 trials allowing for visual search Task 2 absorption into the slack time of the response selection.

Additionally, we tested implication (2) of the alternative hypothesis, i.e. that a motor bottleneck has caused the current data pattern. The probability that a motor bottleneck occurs should be larger under conditions of short IRI compared to large IRI and the slack time of the motor bottleneck should occur rather at short IRI (see De Jong, 1993). Therefore, if a motor bottleneck had occurred in the dual-task situation, we should expect absorption of visual search time into its slack time rather for the short IRI and not so (if at all) for the long IRI at short SOA. To test implication (2), we calculated the IRI at short SOA as the interval between the responses to Task 2 and Task 1 (IRI = RT2 – RT1 + SOA) and performed a median split. If there was no difference in the absorption of visual search processes between the lower and the upper median, then this would not be consistent with the assumption that a motor bottleneck had emerged in the current dual-task situation, since the motor bottleneck should especially occur under conditions of short but not long IRI (see above). Consequently, if we did not find evidence suggesting the existence of a motor bottleneck, then there would be no reason to assume that visual search time of Task 2 was absorbed into the slack time of a motor bottleneck.

Accordingly, for each participant at short SOA, we calculated the IRI as the interval between the responses to Task 2 and Task 1. We ranked the IRI in ascending order and performed a median split so that the lower median corresponded to the short IRI and the upper median to the long IRI. In a next step, we calculated the corresponding RT2 differences between set sizes 18 and 6 depending on the IRI median. Importantly, in Experiment 1, a t-test revealed no significant difference between the RT2 differences of set sizes 18 and 6 across the IRI median split, $t(23) = .708$, $p = .49$. The resulting RT2 differences amounted to 29 ms at short IRI and 47 ms at long IRI. The equivalent t-test in Experiment 2 was not significant either, $t(23) = .533$, $p = .60$, (RT2 differences at short vs. long IRI: M = 46 ms vs. 61 ms). In both experiments, the amount of absorption of visual search Task 2 into the slack time did not depend on the IRI. Considering that the probability of a motor bottleneck to occur should be larger at short IRI compared to long IRI, the findings indicated that the occurrence of a motor bottleneck did not seem very likely in the present dual-task experiments.

All in all, the results of the distribution analyses were not consistent with the alternative explanation that the visual search RT2 would have been absorbed into the slack time of a potential later bottleneck, a motor bottleneck, that could have occurred in case of fast RT1. The analyses showed that the speed of RT1 did not influence the amount of absorption in RT2, which speaks against the idea that the response selection in Task 1 was so fast that the visual search processes in Task 2 started after its end. In addition, the findings did not provide sufficient evidence for the assumption that a potential motor bottleneck has occurred, which would have caused absorption of visual search time into the slack time. The results of the current IRI cannot easily be reconciled with the assumption that a motor bottleneck had caused the observed underadditive interaction between set size and SOA on RT2.

To conclude, the results of both distribution analyses are consistent with the main conclusion of the present study that visual attention in Task 2 can be deployed concurrently with response selection processes in Task 1.

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