



Processing order in dual-task situations: The “first-come, first-served” principle and the impact of task order instructions

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Abstract

When two overlapping tasks are processed, they hit a bottleneck at a central processing stage that prevents simultaneous processing of the two tasks. Thus far, however, the factors determining the processing order of the tasks at the bottleneck are unknown. The present study was designed to (re)investigate whether the arrival times of the two tasks at the central bottleneck are a key determinant of the processing order (cf. Sigman & Dehaene, 2006). To this end, we implemented a visual–auditory dual task with a random stimulus order, in which we manipulated arrival time by prolonging the initial, perceptual processing stage (stimulus analysis) of the visual task and compared the effects of this manipulation with those of one impacting the central bottleneck stage of the visual task. Additionally, we implemented two instruction conditions: Participants were told to respond either in the order of stimulus presentation or in the order they preferred. The manipulation of the visual perception stage led to an increase in task response reversals (i.e., the response order was different from the order of stimulus presentation), whereas there was no such increase when the bottleneck stage was manipulated. This pattern provides conclusive evidence that the processing order at the bottleneck is (at least in part) determined by the arrival times of the tasks at that point. Reaction time differences between the two instruction conditions indicated that additional control processes are engaged in determining task processing order when the participants are expressly told to respond in the order of stimulus presentation.

Keywords Central bottleneck · Processing order · PRP · Dual task · Executive control

A common experience in everyday life is that attempting to carry out two tasks concurrently compromises performance in one or both of these tasks; that is, dual-task costs manifest as an increase in either errors or the time needed to perform the two tasks, as compared to isolated task performance in single-task situations. Dual-task costs are frequently described using the “psychological refractory period” (PRP) paradigm: Two stimuli are presented with a variable, short delay between their onsets (a stimulus onset asynchrony, SOA), and participants

have to make choice reaction time (RT) responses to these stimuli. The standard finding is that the RT to the second (task’s) stimulus (RT2) increases with decreasing SOA, whereas the RT to the first (task’s) stimulus (RT1) is typically unaffected by SOA (for overviews, see Pashler, 1994; Schubert, 2008; Strobach, Schütz, & Schubert, 2015). This RT2 pattern is referred to as the “PRP effect.”

The PRP effect has been attributed to a processing bottleneck that prevents the two tasks from being performed in parallel; specifically, the bottleneck is located at the central processing stage (between perception and response execution), namely the stage of *response selection* (Fig. 1A). Note that there are debates about the nature of the bottleneck, whether it reflects a structural limitation (e.g., Pashler, 1994; Welford, 1952, 1980) or a strategic one (e.g., Hazeltine, Ruthruff, & Remington, 2006; Meyer & Kieras, 1997; Miller, Ulrich, & Rolke, 2009). Whatever the bottleneck’s precise nature, the notion of a central response selection bottleneck accounts for the PRP effect by assuming that, if two tasks are presented with a temporal overlap (i.e., with short SOAs between Stimulus 1 and Stimulus 2), response selection for the two tasks operates serially (whereas the initial stimulus

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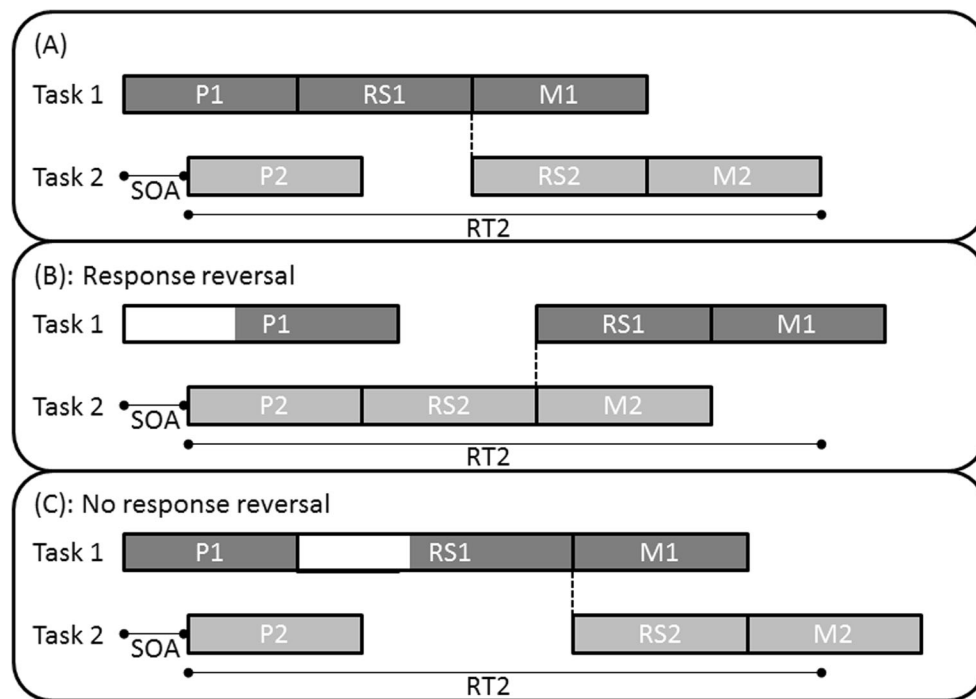


Fig. 1 (A) Central bottleneck model: When two tasks are presented with a temporal overlap, all processing stages are able to run in parallel except for the response selection stage. Task 2 response selection has to wait until response selection is complete for Task 1 (i.e., no response reversal). (B) Response reversal: The later start of perceptual processing in Task 1 leads to the earlier arrival of Task 2 at the bottleneck. Therefore, Task 2 is

processed before Task 1. (C) No response reversal: If the response selection stage of Task 1 is prolonged, Task 1 still arrives at the bottleneck before Task 2 and is therefore processed first. P1 = perception stage of Task 1, RS1 = response selection stage of Task 1, M1 = motor response of Task 1; P2, RS2, and M2 are defined analogously.

perception and final response execution stages of the two tasks can operate in parallel). In other words, selection of the response to the task stimulus presented second has to wait until the first task has exited the bottleneck stage. With decreasing SOA, the overlap between the two tasks increases, effectively prolonging the waiting time for the second task, which translates into longer RT2s.

Although the bottleneck assumption provides a commonly accepted explanation for a variety of findings in dual-task research, one important question remains unresolved: How is the bottleneck mechanism allocated to the two task streams? In other words, which of the two tasks can pass the bottleneck first and which, second, and how is the processing order at the bottleneck determined?

Determination of task order processing: The central arrival time

One key factor thought to determine processing order is the relative arrival times of the two tasks at the bottleneck—that is, the point in time at which the perceptual (stage) processing of the stimulus for a given component task is completed and the stimulus information is forwarded to the central bottleneck stage (Sigman & Dehaene, 2006). The idea is that the processing order at the bottleneck is governed by the “first-come, first-

served” principle: that the component task that arrives first at this stage enters (and occupies) the bottleneck first. Two important predictions follow from this assumption. First, if the two tasks are presented with a short SOA between the respective stimuli (for Tasks 1 and 2), and if some prebottleneck stage (e.g., perception) of Task 1 is prolonged (through some experimental manipulation) for a time longer than the SOA, then the perceptual (stage) output for Task 2 might arrive earlier at the bottleneck—in which case, Task 2 would be the first one to enter the bottleneck stage (Fig. 1B). This prolongation should give rise to an increased frequency of response reversals; that is, participants should respond to Task 2 first more often than in the baseline, “nonprolonged” condition. The second prediction is that if, instead, the (bottleneck) stage of response selection (rather than the stage of perceptual processing) is prolonged for Task 1 (through some appropriate manipulation), this would impact processing only after the point in time at which the task order is determined. Accordingly, such a prolongation should not lead to a change in the processing order, because the perceptual (stage) output for Task 1 would still arrive at the bottleneck prior to the perceptual output for Task 2 (Fig. 1C). In summary, the “first-come, first-served” principle predicts that prolongation of the perception stage for the first-presented task would result in an increased number of response reversals, whereas prolongation of the response selection stage of the same task would not.

Previous research testing predictions of the central arrival time assumption

A first test of the predictions deriving from the arrival time assumption was provided by Sigman and Dehaene (2006). Their participants were presented with an auditory task requiring tone discrimination and a visual task in which participants judged whether a presented number x ($21 \leq x \leq 69$) was less or greater than 45; the task order and the SOA between the task stimuli were varied. The authors manipulated the perception and the response selection stages of the visual task in order to investigate whether these manipulations would yield an increase in the number of response reversals. The duration of the visual perception stage was manipulated by varying the “notation” of the presented numbers (notation manipulation): The numbers were displayed as either digits or numerals (i.e., number words), where the latter are thought to require more time to perceptually analyze (Sigman & Dehaene, 2005). The duration of the central response selection stage was (assumed to be) manipulated by varying the distance of the number x from 45 (distance manipulation): The classification of x (for response selection) was thought to take longer for numbers closer to 45 than for numbers farther away. For trials on which the visual (number) task was presented first, Sigman and Dehaene (2005) indeed found a significantly increased proportion of response reversals when the perception stage was prolonged; by contrast, changing the distance of the number x from 45 had no effect on response order.

First, the arrival time assumption might not be the only prebottleneck factor that influences the task processing order. As is elaborated in the General Discussion and by Leonhard and Ulrich (2011), the detection time for the stimuli is an alternative factor that could influence this order and is located before the central bottleneck. Second, the findings of Sigman and Dehaene (2006) were not entirely conclusive, because of the specific way they manipulated the duration of the perception (digits vs. numerals) and central bottleneck (distance to 45) stages. Although these manipulations influenced the overall processing duration of the visual task, it is not completely clear whether they exclusively impacted the intended target stages. Such a specific impact of task manipulations on target stages, however, would be required in order to come to firm conclusions about the task order processing versus the component task processing stages. For instance, with regard to the notation manipulation, question is unresolved whether this manipulation exclusively affects the perception stage or whether it also affects the central bottleneck. Whereas interference-based phenomena such as the Stroop effect (e.g., MacLeod, 1991) suggest that visual word processing is automatic, and thus occurs at the perceptual stage, PRP studies indicate that this processing is subject at least in part to central bottleneck processing. For example, using the PRP paradigm, McCann, Remington, and Van Selst (2000) found

that the effects of word frequency in a lexical decision task and a word-naming task on RT2 were additive with those of an SOA manipulation between the two tasks. In other words, for the second task, a fixed amount of time was added across the different SOA levels—which, according to the “locus-of-slack” logic in PRP research, implies that some constant part of visual word processing in Task 2 was subject to central bottleneck processing: The stimulus could not be processed in parallel with (i.e., without interference from) the processes in Task 1 (Lien, Ruthruff, Cornett, Goodin, & Allen, 2008; McCann & Johnston, 1992). Similarly, the notation manipulation of Sigman and Dehaene (2006) also produced an additive effect with SOA when the visual task was presented as Task 2 [see their Table 1: $F(7, 84) = 1.78, p = .1$]. Thus, some constant part of the manipulation effect prolonged processes after the perception stage (e.g., the central stage). Given these findings, with regard to the study of Sigman and Dehaene (2006), we cannot conclusively infer that the effect of the notation manipulation exclusively affected processes before the central bottleneck. Accordingly, it is difficult to specify the time demands of prebottleneck and bottleneck processing for the notation manipulation in their study.

Thus, the first aim of the present study was to test the predictions of the “first-come, first-served” principle when the stimuli and the perception stage of the visual task were manipulated in a way that would allow a more direct attribution of the experimental manipulations to the targeted processing stage (Sanders, 1980). To realize this, we applied a well-established type of perceptual (stage) manipulation to a visual task in the PRP paradigm with varying (visual and auditory) stimulus presentation order: We varied the luminance of the visual stimuli while holding the stimulus background luminance constant (instead of varying the formats of the visual stimuli themselves, as had been done by Sigman & Dehaene, 2006). This contrast manipulation should target relatively early processes of perceptual stimulus encoding (Sanders, 1990). There is ample evidence that manipulations of stimulus contrast lengthen the perceptual stage (e.g., McCann & Johnston, 1992; Pashler, 1984, 1994); for a demonstration of the appropriateness of this manipulation for modulating the perception stage in a temporal-order judgment task (requiring mere judgment of the stimulus presentation order) as well as in a dual-task situation (requiring discriminative responses to the stimuli), see also Hendrich, Strobach, Buss, Müller, and Schubert (2012) and Hein and Schubert (2004).

Furthermore, Sigman and Dehaene (2006) employed a specific version of the PRP dual-task situation in which participants were explicitly instructed to respond “accurately and as fast as possible to each [stimulus] as it arrived” (p. 1236). This particular instruction might induce a bias toward sequential handling of the response selection processes, according to Meyer and Kieras (1997; see also Schumacher et al., 2001) and their executive process/interactive control (EPIC) model;

Table 1 Error rates in percent of Experiments 1 and 2 for the visual and auditory tasks, SOAs -400 to 400, the order instruction versus the free-choice instruction and the two contrast conditions (strong vs. weak, Exp. 1) and mapping conditions (compatible vs. incompatible, Exp. 2)

Experiment	Task	Instruction	Contrast (Exp. 1)/ Mapping (Exp. 2)	SOA						
				Visual task presented first				Auditory task presented first		
				-400	-120	-60	0	+60	+120	+400
Experiment 1	Visual	order	strong	3.5	4.9	4.5	5.7	4.9	6.6	5.6
			weak	7.8	8.0	7.8	6.1	7.1	5.3	6.9
		free-choice	strong	2.4	3.1	3.1	4.0	3.5	4.1	3.8
			weak	6.4	7.5	6.9	4.3	4.8	4.7	6.0
	Auditory	order	strong	9.0	12.4	13.6	11.3	9.3	11.6	7.3
			weak	13.1	13.4	15.9	13.7	10.5	9.1	7.8
		free-choice	strong	11.1	11.6	10.6	11.1	11.7	9.2	9.5
			weak	12.0	11.0	9.1	11.7	6.8	9.2	8.5
Experiment 2	Visual	order	compatible	2.9	3.5	4.5	4.4	4.5	4.9	5.1
			incompatible	10.3	10.9	11.3	12.1	13.8	10.9	10.8
		free-choice	compatible	6.7	4.9	2.2	4.4	4.7	4.1	3.8
			incompatible	9.3	6.8	10.6	6.5	8.1	6.4	10.2
	Auditory	order	compatible	11.4	11.3	11.8	12.5	10.3	9.9	9.4
			incompatible	9.3	7.6	6.6	8.2	7.4	6.7	4.0
		free-choice	compatible	10.3	10.2	8.2	6.8	8.2	5.9	5.4
			incompatible	11.6	9.2	9.9	6.5	8.8	6.8	6.1

this strong bias might be the very core of the “first-come, first-served” principle (but see Leonhard, Ruiz Fernández, Ulrich, & Miller, 2011; Ruiz Fernández, Leonhard, Rolke, & Ulrich, 2011). In other words, participants may have focused on stimulus presentation in order to decide upon the response order because they took the instruction as a request to do so. Accordingly, it cannot be ruled out that Sigman and Dehaene’s (2006) findings are an “artifact” of the sequential task instructions. Alternatively, presenting instructions without a bias toward sequential handling might provide more favorable conditions in which to test the “first-come, first-served” principle.

A second aim of the present study was to address this issue by manipulating the perception stage in a PRP situation (with varying task order) under two different instruction conditions: In one condition, as in Sigman and Dehaene’s (2006) study, participants were instructed to respond to the tasks in the order they were presented—henceforth referred to as *order* instructions. In the other, *free-choice* instruction condition, participants were told to freely decide on the order in which to respond to the two stimuli. We reasoned that the latter instructions would provide more favorable conditions for testing the “first-come, first-served” principle and would be more diagnostic for testing the impact of the perception stage manipulation. If similar effects of this manipulation were obtained with both types of instructions, this would be indicative of

the arrival time logic reflecting a general principle, rather than applying only under specific task instructions.

Next, we consider Sigman and Dehaene’s (2006) distance manipulation by varying the distance of number x from 45. Recent studies have shown that semantic memory retrieval during number classification at least partly can occur simultaneously with bottleneck processing in another task (e.g., Fischer, Miller, & Schubert, 2007). Furthermore, Oriet, Tombu, and Jolicœur (2005) used a PRP situation with a tone judgment task as Task 1 and a number judgment task as Task 2 (“Is the presented number smaller or larger than 5?”). The authors focused on the interaction between numerical distance and task overlap (SOA) on RT2. If processes of (semantic) memory retrieval in Task 2 do not involve the central bottleneck and can operate in parallel with Task 1, then the effect of numerical distance should decrease at short SOAs. The reason is that, at short SOAs, the extra time needed for processing numbers nearer to the reference number should be absorbed into the “slack”—that is, into the time period during which Task 2 central processing has to wait because Task 1 occupies central processing. At long SOAs, by contrast, the full effect of the numerical distance manipulation should become manifest in the RT2s (Hein & Schubert, 2004; Lien & Proctor, 2000; McCann & Johnston, 1992; Pashler & Johnston, 1989). Such an underadditive interaction of the effects of numerical distance and SOA on RT2 is exactly what Oriet et al.

found. Their results thus show that semantic memory retrieval can in fact proceed in parallel with central bottleneck processing in another task. Note that Sigman and Dehaene's (2006) results in part "echo" these findings: When the visual task was presented second, the effect of distance was absorbed into the slack for shorter SOAs (SOAs < 400 ms), and the combination of SOA and the distance manipulation showed a strong trend toward an underadditive interaction across all SOA levels [$F(7, 84) = 1.98, p = .067$]. This absorption may indicate that their distance manipulation, rather than exclusively impacting central bottleneck processing, did involve other, noncentral processes as well. This raises questions about the conclusiveness of their findings as to bottleneck arrival time playing a key role in determining task order.

Given this result, the third aim of the present study was to test the predictions of the arrival time "first-come, first-served" principle when the response selection stage of the visual task is manipulated in a way that permits the effects to be attributed more directly to this stage (Sanders, 1980). In particular, we manipulated the compatibility between the stimulus and response information (Duncan, 1979; McCann & Johnston, 1992)—on the basis of a recent study that successfully demonstrated the appropriateness of this manipulation as a modulation of the response selection stage in a dual-task situation (Hendrich et al., 2012).

In summary, we manipulated visual stimulus contrast in Experiment 1, and stimulus–response information compatibility in Experiment 2, to directly target the perception and response selection stages of the visual task, respectively—in order to clarify whether the arrival time "first-come, first-served" principle does indeed determine the order in which the tasks are processed in dual-task scenarios. Importantly, in both experiments these manipulations were realized under both an *order* and a *free-choice* instruction condition, to rule out the possible shortcomings of Sigman and Dehaene's (2006) study, which did not control for potential instruction-related effects on the determination of task order.

Experiment 1

In Experiment 1, in dual-task trials, a visual and an auditory discrimination task were presented with a variable task order (e.g., de Jong, 1995; Sigman & Dehaene, 2006; Töllner, Strobach, Schubert, & Müller, 2012). The visual task required number discrimination: Participants had to indicate the number (i.e., 2, 5, 9) presented on the screen with a keypress response. In the auditory task, participants discriminated three tones, of low, middle, and high frequency, respectively. To manipulate the perception stage of the visual task, we varied the contrast of the number stimuli against the background: Numbers were shown either in white (*strong-contrast condition*) or in light gray (*weak-contrast condition*) on a dark

gray background. The contrast reduction in the latter (as compared to the former) condition slowed RTs by 93 ms in a pilot study. To check whether the contrast manipulation did impact the time required for visual processing, we examined the *point of subjective simultaneity* (PSS) of the visual and auditory stimuli (Hendrich et al., 2012; Shi, Chen, & Müller, 2010). Psychophysical research has shown that visual stimuli generally need more time to reach central processing than do auditory stimuli (e.g., Boenke, Deliano, & Ohl, 2009; Spence, Shore, & Klein, 2001). In other words, a visual stimulus would have to be presented earlier (i.e., with a negative inter-stimulus interval, ISI) than an auditory stimulus to be perceived as simultaneous. In the present study, we used the PSS to check whether the processing time required by the visual stimulus to reach central processing was longer in the weak- than in the strong-contrast condition. The perception stage should be expedited in the strong-contrast condition. Accordingly, the PSS between the visual and auditory stimuli should be characterized by an ISI that was reduced in absolute terms relative to the weak-contrast condition. If the arrival time "first come, first serve" principle is correct, the RT difference between the strong- and weak-contrast conditions should be longer than the shortest SOA in our study (60 ms)—leading to an increased incidence of response reversals under (at least) the weak-contrast condition for this SOA when the visual task is presented first.

We further manipulated the instructions: Participants received either an order instruction or a free-choice instruction. If the particular (order) instruction used by Sigman and Dehaene (2006) does induce participants to (strategically) determine processing order by arrival time, we should expect to find an increased number of response reversals at short SOAs under the order as compared to the free-choice instructions.

Furthermore, from the central bottleneck model (Pashler, 1994; Ruthruff, Pashler, & Hazeltine, 2003), a number of specific predictions can also be derived about the RTs under both instruction conditions. When the visual task is presented first, prolonging its perception stage should produce a slowing of RT1. This increase in RT1 should also slow RT2, because Task 2 would have to wait longer at the bottleneck before it can be processed; given the rather restricted range of SOAs introduced in the present study (i.e., SOAs ≤ 400 ms, as compared to SOAs $\leq 1,000$ ms in other studies, such as Sigman & Dehaene, 2006), we predicted that the effects of the manipulation in (the visual) Task 1 would propagate to RT2 (auditory task) at longer (i.e., nearer 400 ms) as well as at the short SOAs—that is, essentially an additive effect of SOA. When the visual task was presented second, any prolongation of its perception stage should fall into the "slack" (i.e., waiting time) created by Task 1 occupying bottleneck processing. Accordingly, we should observe no increase in RT2 (visual task) with prolonged visuo-perceptual processing; because of the restricted SOA range, this again should be the case for both short and long SOAs.

Concerning the different instructions (order vs. free choice), RTs were expected to be generally increased under the order instruction condition (de Jong, 1995; Szameitat, Lepsien, von Cramon, Sterr, & Schubert, 2006; Umiltà, 1988), because this condition would likely involve more active control of the two task-processing streams.

Method

Participants

Forty participants, all of whom were students at LMU Munich, took part in Experiment 1, 20 in each instruction condition. In the *order* instruction condition, 13 of the participants were female (mean age = 25.1 years, $SD = 2.9$ years); in the *free-choice* condition, 14 of the participants were female (mean age = 26.6 years, $SD = 4.5$ years). All participants (except one) were right-handed, and all reported normal or corrected-to-normal vision and hearing. They received either course credits or payment (€8/h) for their service. The experimental session lasted approximately 90 min.

Apparatus

Participants were tested individually in a sound-attenuated, darkened room. They sat in front of a CRT monitor (85-Hz frame rate) and wore headphones. Responses were given on a QWERTZ keyboard. The experimental code was written for the Presentation software (Version 14.4 02.24.10) and was run on a Dell Optiplex GX620 with Windows XP Professional.

Stimuli

The visual stimulus set consisted of three digits—2, 5, or 9¹—that were presented with either strong contrast (white font color, 55 cd/m²) or weak contrast (gray font color, 0.11 cd/m²) against a dark-gray background (0.09 cd/m²; dark gray instead of black was used in order to minimize visual aftereffects). At a viewing distance of 55 cm, each digit subtended a visual angle of $1.0^\circ \times 1.5^\circ$. The auditory stimuli were three sine-wave tones with frequencies of 250, 500, and 1000 Hz,

¹ The rationale to select 2, 5, and 9 as the visual stimuli was that, in addition to the middle value of the single digits (i.e., 5), we aimed to include a mix of single digits with an extremely high (i.e., 9) or low (i.e., 2) value, to increase the load on the selection process. Such a loading of selection processes is a requirement for investigating task order processing. One alternative would be to combine the digit stimulus “1” with the other digits. However, the selection of 1 in combination with other digits might lead to an automatic perceptual classification of this stimulus without a capacity-limited selection processes; such selection would be required, however, for us to investigate the effect of task order at the central bottleneck. The classification of “1” in contrast to other digit stimuli (e.g., “5” or “9”) might be rather automatic, since the structural configuration of “1” (e.g., exclusively straight lines) clearly distinguishes this stimulus from other stimuli that are curved.

respectively, and a volume of 58 dB. They were presented via headphones.

Design and procedure

Each trial started with the presentation of a white fixation point for 500 ms in the screen center. Then, 600 ms after the disappearance of the fixation point, either the visual or the auditory stimulus was presented, and the second stimulus followed after a variable SOA: 0 ms (i.e., simultaneous stimulus presentation), 60 ms, 120 ms, or 400 ms. Both stimuli were presented for 200 ms. For the auditory task, participants were asked to respond to the stimuli by pressing the “y,” “x,” or “c” key for tones of low, middle, or high frequency with their left-hand ring, middle, and index finger, respectively. For the visual task, the participants responded by pressing the comma, period, and hyphen keys for “2,” “5,” and “9” with the right-hand index, middle, and ring finger, respectively. Each trial lasted 4,500 ms.

Participants completed two practice blocks for the single tasks (15 trials each) and one practice block with dual-task trials (20 trials). For the main experiment, they completed six blocks of 63 trials each; these 63 trials resulted from all possible combinations of SOA (± 400 , ± 120 , ± 60 , 0 ms), visual stimulus (“2,” “5,” “9”), and auditory stimulus (250, 500, 1000 Hz), which were presented in randomized order. Feedback on the correctness of the responses was given only in the practice blocks.

Three blocks with strong-contrast and three with weak-contrast visual stimuli were presented in alternating order. (Contrast was varied between blocks in order to modulate the visual task in similar ways in Exps. 1 and 2. In Exp. 2, this between-block modulation was the only plausible procedure through which to realize a response-mapping manipulation, which is why we also modulated contrast between blocks in Exp. 1.) Half of the participants started with a strong-contrast and half with a weak-contrast block. In the order condition, participants were instructed to respond “as fast and as accurately as possible to each stimulus as it arrived.” In the free-choice condition, by contrast, they were told to respond “as fast and as accurately as possible to each of the stimuli”; additionally, they were asked not to respond in a systematic manner, such as by always performing one task first or regularly alternating the task order between trials. Response order, RTs, and error rates were measured as dependent variables.

Results

Trials with RTs outside three standard deviations (SDs) from the individual condition means were excluded from the analysis. Trials on which the response(s) to one or both of the

component tasks was/were incorrect or omitted (error trials) were also excluded from the analyses of PSS, response order, and RTs. That is, we excluded 14.5% of the trials in the order instruction condition (5.1% removed due to *SD* outliers; 9.4% removed due to errors) and 13.0% of the trials in the free-choice instruction condition (3.9% removed due to *SD* outliers; 9.1% removed due to errors). We corrected *F* values (Greenhouse–Geisser) and *t* tests for unequal variances (Levene correction), where necessary.

Point of subjective simultaneity

To estimate the PSS—that is, the time point at which participants responded to the tone first on 50% of the trials—we plotted, for each participant, the percentage of “tone responded to first” trials (note that, in the other trials, participants had responded to the tone second) as a function of SOA and fitted a logistic regression to each plot. For each contrast and instruction condition, the transition threshold between the visual and auditory stimuli—that is, the point at which visual and auditory stimuli were responded to first equally frequently—was then determined by estimating the 50% point on the logistic function (Treutwein & Strasburger, 1999). The resulting PSS values were submitted to an analysis of variance (ANOVA) with Contrast (weak vs. strong contrast) as a within-subjects factor and Instructions (order vs. free-choice) as a between-subjects factor.

In the strong-contrast condition, the mean PSS was –45 ms, which compares with –114 ms in the weak-contrast condition. This shift of the PSS (mean of 69 ms) in the latter (vs. the former) condition was significant: main effect of contrast, $F(1, 38) = 4.202, p < .05$. In other words, with weak contrast, the visual stimulus needed to be given a greater head start (of 69 ms) in order to be perceived as simultaneous with the auditory stimulus, as compared to the strong-contrast condition. There were no significant (main effect or interaction) effects of instructions. These findings demonstrate that the contrast manipulation was appropriate to modulate the time required for processing the visual stimulus from its presentation to central processing, consistent with Hendrich et al. (2012).

Response order

As an index of response order, we examined the percentage of trials on which participants responded to the tone first (“tone responded to first” trials) in a mixed-measures ANOVA with Contrast (weak vs. strong) and SOA (0, –60, –120, –400 ms) as within-subjects factors and Instructions (order vs. free-choice) as a between-subjects factor. To distinguish between the two different task orders (“tone presented first” vs. “number presented first”), trials in which the number was presented first were marked by negative SOAs, and trials in which the tone was presented first were marked by positive

SOAs. Figures 2A and 2B illustrate the percentages of “tone responded to first” trials for the two instruction conditions.

As expected, contrast yielded a main effect, $F(1, 38) = 22.734, p < .01$: The percentage of “tone responded to first” trials was higher with weak than with strong contrast (61.0% vs. 54.6%). This indicates that, as compared to the visual stimulus, processing of the auditory stimulus finished overall faster (evidenced by the “tone responded first” percentage exceeding 50%), with this effect being particularly marked under the weak-contrast condition. Additionally, the Contrast \times SOA interaction was significant, $F(6, 228) = 3.402, p < .01$: The percentage of “tone responded to first” trials was significantly increased in the weak- (as compared to the strong-) contrast condition for the SOAs of –400, –120, –60, 0, and 60 ms [$ts(39) > 2.185, ps < .05$], but not for the other positive SOAs. Recall that negative SOAs mean that the visual stimulus was presented first; nonetheless, the low (vs. high) contrast of the visual stimulus yielded increased percentages of “tone responded to first” trials. Also as expected, the percentage of “tone responded to first” trials increased with increasing SOA [main effect of SOA: $F(6, 228) = 166.541, p < .01$]: It was lowest for the SOA of –400 ms (14.5%) and highest for the 400-ms SOA (92.2%). Most importantly, the effect of SOA was moderated by instructions, $F(6, 228) =$

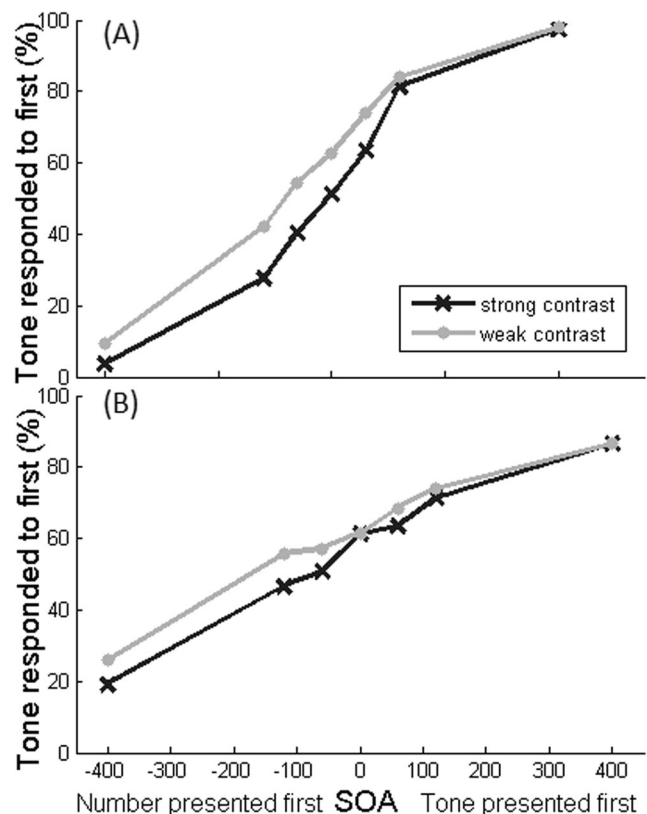


Fig. 2 Percentages of trials in Experiment 1 on which participants responded to the auditory task first for each condition (strong/weak contrast) and stimulus onset asynchrony (SOA). (A) Order instructions. (B) Free-choice instructions

8.344, $p < .01$. The number of response reversals was higher under the free-choice than under the order instructions at “extreme” SOAs, with significant differences (in the percentages of reversals) between the instruction conditions at the SOAs of -400 ms [$t(24.520) = -3.657$, $p < .01$], -120 ms [$t(38) = -2.820$, $p < .01$], and 400 ms [$t(20.636) = 3.857$, $p < .01$]. This can be taken to indicate that in the free-choice condition, participants operated more relaxed control of task order at the extreme SOAs. Note that this pattern was not modulated by visual stimulus contrast. The Instruction \times SOA \times Contrast interaction was far from significance, $F(6, 228) < 1$, nor were there any other significant (main or interaction) effects.

RTs

RT performance was analyzed in order to examine whether the RTs “complied” with the central bottleneck model. Because the model makes different predictions regarding the effects of the various (task) manipulations, depending on the order of the component tasks, RTs were examined separately for trials in which the “visual task was presented and responded to first” (VPRF) and trials in which the “auditory task was presented and responded to first” (APRF). For the SOA 0-ms condition, in which there was no stimulus-defined processing order, trials were classified according to the order in which participants responded to the tasks (i.e., SOA 0-ms trials on which the visual task was responded to first were analyzed together with the VPRF trials, and trials on which the auditory task was responded to first were analyzed with the APRF trials). The RTs for the VPRF and APRF trials, which are depicted in Figs. 3 and 4, were subjected to mixed-measures ANOVAs with the within-subjects factors Contrast (weak vs. strong) and SOA (0, -60 , -120 , -400 ms) and the between-subjects factor Instructions (order vs. free-choice).

VPRF trials

RT1 (visual task) According to the central bottleneck model, RT1 should be unaffected by SOA (while being perhaps generally prolonged by additional processes of order control; e.g., Sigman & Dehaene, 2006). However, RT1 should be prolonged in the weak- (as compared to the strong-) contrast condition. The analyses confirmed the central-bottleneck predictions: SOA had no influence on RT1, $F(3, 105) < 1$, but the manipulation of contrast had a significant effect, $F(1, 35) = 34.688$, $p < .01$: RT1 was increased overall in the weak- as compared to the strong-contrast condition (1,266 vs. 1,175 ms). Furthermore, instructions had a significant effect on RT1, $F(1, 35) = 5.724$, $p < .05$: RT1 was longer under the order than under the free-choice instructions (1,324 vs. 1,117 ms). There were no significant interactions.

RT2 (auditory task) Because of propagation of the contrast effect on (visual) RT1 to the (auditory) task presented second, a significant effect of contrast on RT2 was expected and was confirmed by the data, $F(1, 35) = 23.726$, $p < .01$: RT2 was 1,535 ms in the weak-contrast condition, as compared to 1,453 ms in the strong-contrast condition. Additionally, RT2 increased with decreasing SOA, $F(3, 105) = 66.062$, $p < .01$, demonstrating the typical PRP effect (e.g., Pashler, 1994; Schubert, 1999). Similar to RT1, instructions also yielded a main effect on RT2s, $F(1, 35) = 4.769$, $p < .05$: RT2 was longer with the order than with the free-choice instructions (1,602 vs., 1,385 ms). The interactions were nonsignificant, indicative of an additive effect of the (Visual Task 1) contrast manipulation and SOA.

APRF trials

RT1 (auditory task) The analysis of RT1s revealed a main effect of instructions, $F(1, 35) = 6.587$, $p < .05$: RT1 was longer with the order than with the free-choice instructions (1,380 vs. 1,171 ms). The main effect of contrast was also significant, $F(1, 35) = 4.266$, $p < .05$, due to slightly longer RT1s in the weak- than in the strong-contrast condition (1,290 vs. 1,261 ms). This contrast effect was modulated by instructions, $F(1, 35) = 4.661$, $p < .05$: The effect of contrast was

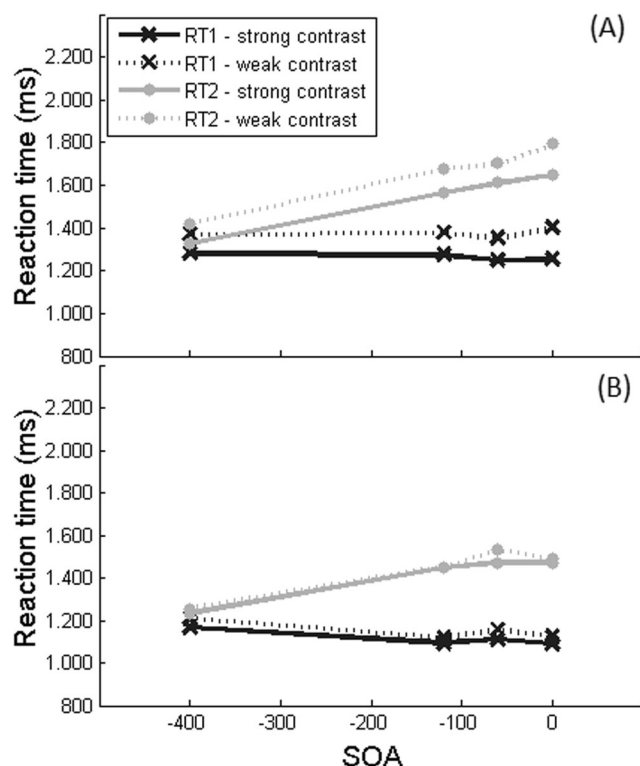


Fig. 3 Reaction times to the visual and auditory tasks for the trials in which the visual task was presented first and responded to first at different levels of stimulus onset asynchrony (SOA) in Experiment 1. (A) Order instructions. (B) Free-choice instructions.

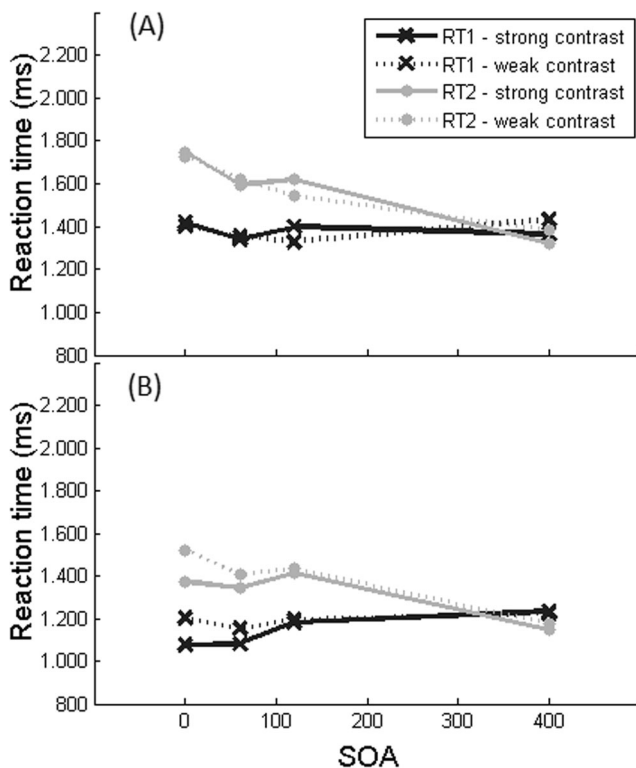


Fig. 4 Reaction times to the visual and auditory tasks for the trials on which the auditory task was presented first and responded to first at different levels of stimulus onset asynchrony (SOA) in Experiment 1. (A) Order instructions. (B) Free-choice instructions.

evident only with the order instructions. This may indicate that, under the order instructions, participants were especially sensitized to the order of the stimuli, with a stronger visual stimulus contrast helping to speed up the task order decision. There was also an effect of SOA, $F(1, 35) = 4.266, p < .05$; that is, RT1 was not completely unaffected by the interval between the two tasks. Specifically, RT1 was longer with an SOA of 400 ms than with the shorter 60- and 120-ms SOAs, which fits with the notion of “response grouping” (Fitts, 1954; Miller & Ulrich, 2008; Pashler & Johnston, 1989; Ulrich & Miller, 2008); in this analysis, participants showed grouped responses with an interresponse interval of < 100 ms in 5.5% of the trials. In that case, participants did not execute R1 immediately after it had been selected, but delayed its execution in order to group it with the R2. Under conditions of longer SOA, participants needed to wait longer for R2, which explains the SOA effect on RT1. Response grouping is also likely responsible for the three-way, Contrast \times SOA \times Instructions interaction, $F(3, 114) = 4.030, p < .001$: There was no effect of instructions at the longest SOA (weak contrast) or at the two longest SOAs (strong contrast). No other interactions were significant.

RT2 (visual task) The analysis of RT2s revealed a main effect of contrast, $F(1, 35) = 4.311, p < .05$, with longer RTs in the

weak- than in the strong-contrast condition (1,465 vs. 1,432 ms). The main effect of instructions was also significant, $F(1, 35) = 6.234, p < .05$, with generally longer RT2s under the order than under the free-choice instructions (1,569 vs. 1,328 ms). Furthermore, contrast and instruction interacted, $F(1, 35) = 5.513, p < .05$: As in the RT1 analysis, the contrast effect manifested only with the order (but not with the free-choice) instructions—in accord with the assumption that these instructions expressly directed participants’ attention to stimulus order, with a stronger stimulus contrast permitting a faster order decision. The main effect of SOA was also significant, $F(3, 114) = 81.044, p < .001$: RT2 increased with decreasing SOA (i.e., the PRP effect). Finally, consistent with the RT1 analysis, the Contrast \times SOA \times Instructions interaction was significant, $F(3, 114) = 4.030, p < .001$: We found no effect of instructions at the longest SOA (weak contrast) or at the two longest SOAs (strong contrast). This mirrors the same pattern observed for RT1, supporting an interpretation in terms of response grouping. No further interactions were significant. In sum, despite some minor deviations from the predictions of the central bottleneck model (see also below), the data provide evidence supporting an impact of instructions on task processing.

Error rates

An ANOVA of the error rates (Table 1), also with the within-subjects factors Task (visual task vs. auditory task), Contrast (weak vs. strong), and SOA (0, – 60, – 120, – 400 ms) and the between-subjects factor Instructions, revealed that participants overall made more errors in the auditory than in the visual task (10.8% vs. 5.3%), $F(1, 38) = 19.615, p < .01$. Moreover, the main effect of SOA was significant, $F(6, 228) = 3.847, p < .01$, reflecting differential error rates between the SOAs of – 120 ms (9.0%) and 400 ms (6.9%), $t(39) = 3.472, p < .01$. Weak contrast led to a significant increase in errors for the visual task, $t(39) = -2.208, p < .05$, but not for the auditory task, $t(39) < 1$, giving rise to a significant Task \times Contrast interaction, $F(1, 38) = 4.066, p = .05$. The Task \times SOA interaction was also significant, $F(6, 228) = 4.539, p < .01$: For the visual task, the error rates did not differ significantly among the individual SOAs, $F(6, 228) < 1$; for the auditory task, by contrast, there was a main effect of SOA, $F(6, 228) = 6.529, p < .001$: Participants made more errors on “number presented first” trials (negative SOAs) than on “tone presented first” trials (positive SOAs). Potentially, tone information decayed when the auditory task was Task 2 during visual task processing, whereas this was not the case when the auditory task was Task 1 (Leonhard et al., 2011). The significant Contrast \times SOA interaction, $F(6, 228) = 2.701, p < .05$, was due to increased error rates in the weak- versus the strong-contrast condition at the – 400-ms SOA ($p < .05$), whereas no contrast-dependent differences emerged at any of the other SOAs ($ps > .09$). No other interactions were significant.

Discussion

Experiment 1 was designed to investigate two questions: First, whether prolongation of the perception stage of the first-presented task (in a dual-task situation) would yield an increase in response reversals in the weak- as compared to the strong-contrast condition, as is predicted by the arrival time “first-come, first-served” principle; second, whether the type of instructions would affect the dual-task response behavior—in particular, whether a free-choice instruction condition would provide evidence in support of the arrival time hypothesis, as order instructions had for Sigman and Dehaene (2006). Explicit order instructions might have induced a strategy biasing participants to respond to the two tasks in an order following the arrival time principle. Experiment 1 showed that prolongation of the prebottleneck stage of the visual task indeed affected the processing order at the bottleneck; in particular, when the visual task was presented first and the perception stage for the visual task was prolonged (due to weak stimulus–background contrast), participants produced more response reversals. Importantly, increased and equivalent percentages of response reversals were observed with both (the order and free-choice) types of instructions, consistent with access to the bottleneck being determined in the same way after completing the perception stage for both instruction conditions. This demonstrates that the arrival time principle not only applies under the order instruction condition but generalizes to free-choice conditions, as well.

Interestingly, though, at long SOAs participants produced generally more response reversals under the free-choice than under the order instruction. This points to a generally reduced reliance of task control on stimulus order under free-choice conditions. Under order instructions, by contrast, additional control processes were likely activated (de Jong, 1995; Szameitat et al., 2006; Umiltà, Nicoletti, Simion, Tagliabue, & Bagnara, 1992) that may have made participants rely more consistently on the presentation order of the stimuli (which is given by the SOA). The increased involvement of control processes is also evidenced by the generally slower RTs in the order (than in the free-choice) instruction condition. Although participants, under free-choice instructions, displayed more flexibility in their choice of response order at long SOAs, the frequency of response reversals was not modulated by the contrast manipulation—that is, a manipulation of perceptual processing time (recall that the triple SOA \times Instruction \times Contrast interaction was nonsignificant). Accordingly, if participants in the free-choice condition followed the stimulus presentation order for task processing (note that they may not have done so), access to the bottleneck was determined by the central arrival time principle in the same way as in the order instruction condition.

A further finding worth considering relates to the RT analysis: RTs in general showed the classical PRP effect, in which

RT2 increased with decreasing SOA. When we focused on RT performance in VPRF trials, participants needed significantly more time to respond to the visual task under weak- (than under strong-) contrast conditions. Such a slowing was also evident in the RTs to the second-presented, auditory task. The latter result is consistent with the assumption that the contrast RT effect in the visual task (RT1) propagates, via the bottleneck mechanism, to the time required to respond in the auditory task (RT2).

In APRF trials, the manipulation of the perception stage of the second-presented (visual) task had an effect on RT1 as well as on RT2 under the order instruction condition. This is consistent with the view that the order instructions explicitly directed participants’ attention to stimulus order when they were deciding on the task order (as compared to the free-choice instructions). Thus, a stronger perceptual contrast of the visual stimulus might speed up the order decision (under order vs. free-choice instructions), explaining the contrast effect on RTs in the order instruction condition. Nevertheless, it is important to note that the general picture of response reversals confirms that, in both conditions, bottleneck access was determined by the “first-come, first-served” principle.

Experiment 2

In Experiment 2, the processing duration of the response selection stage was varied in order to assess how this manipulation would influence the order of task performance and the RTs in our dual-task situation. The duration of the response selection stage was manipulated by changing the stimulus–response mapping in the visual task (Duncan, 1979; McCann & Johnston, 1992): In one condition, the mapping of the stimuli to the response keys was compatible (i.e., the numbers from small to large were mapped to response keys from left to right), whereas it was incompatible in the other condition (i.e., the numbers from small to large were not mapped to response keys from left to right). A pilot study showed that this manipulation led to an RT increase in the incompatible versus the compatible condition of about 100 ms, which is longer than the shortest SOA (60 ms) in our PRP experiments.

According to the “first-come, first-served” principle, the output of the earlier-completed perception stage should enter bottleneck processing first. However, prolongation of the response selection stage for the visual task would not be expected to influence the arrival of the perceptually (i.e., visually) encoded and analyzed stimulus at the bottleneck, as compared to the stimulus in the auditory task. Consequently, response selection prolongation should not influence the PSS or the processing order of the two tasks.

Experiment 2 was also run under two instruction conditions, order and free-choice, in order to test whether the

“first-come, first-served” principle would be valid under both conditions. Evidence for the impact of central arrival time under both dual-task instructions would provide further support for the generalizability of the “first-come, first-served” principle.

Concerning RTs and the central bottleneck model (Pashler, 1994), the manipulation of the response selection stage should lead to longer RT1s in the condition with an incompatible (vs. a compatible) stimulus–response mapping if the visual task was presented and responded to first. This prolongation should then propagate to the subsequent auditory task. By contrast, for trials on which the auditory task was presented and responded to first, RT1 should not be influenced by the manipulation of the subsequently presented visual task; however, RT2 should be prolonged by the incompatible mapping, with a comparable slowing for all SOA levels (additive interaction). Analogous to Experiment 1, these predictions should hold for both the order and free-choice instructions if participants performed the two component tasks using the same order strategy. Nevertheless, RT1 and RT2 were expected to be increased under the order instructions, since this condition would involve enhanced control of the two task-processing streams.

Method

Participants

Thirty-nine students at LMU Munich took part in Experiment 2. Twenty-two of them were assigned to the order instruction condition (18 females, four males; mean age = 23.9 years, $SD = 3.8$ years), and 17 to the free-choice instruction condition (12 females, five males; mean age = 24.7 years, $SD = 8.4$ years). All participants were right-handed (except for one), all reported normal or corrected-to-normal vision and normal hearing, and all received course credit or payment for their service (€8/h).

Apparatus, stimuli, design, and procedure

The apparatus, stimuli, design, and procedure were as in Experiment 1, except that, instead of stimulus contrast, the stimulus–response mapping was manipulated in the visual task. In the compatible condition, the mapping was the same as in Experiment 1; in the incompatible condition, the comma, period, and hyphen keys were associated with the numbers 5, 9, and 2, respectively. Prior to the experiment, participants performed five practice blocks. First, they performed one block each for the auditory task, the visual task with compatible mapping, and the visual task with incompatible mapping (20 trials each). In Practice Blocks 4 and 5, participants performed 30 dual-task trials apiece with the compatible and with the incompatible mapping.

Results

The data handling was similar to that in Experiment 1. In all, 12.8% (3.4% removed due to SD outliers; 9.4% removed due to errors) and 11.6% (2.7% removed due to SD outliers; 8.9% removed due to errors) of trials were removed from the analyses of PSS, response order, and RTs in the order and free-choice conditions, respectively.

PSS

The PSS data were computed as in Experiment 1. An ANOVA with the factors Mapping (compatible vs. incompatible) and Instructions (order vs. free-choice) revealed no significant (main or interaction) effects—consistent with Hendrich et al. (2012).

Response order

Response order was examined in a mixed-measures ANOVA with Mapping (compatible vs. incompatible) and SOA (0, –60, –120, –400 ms) as within-subjects factors and Instructions (order vs. free-choice) as a between-subjects factor. As can be seen from Fig. 5, there was no difference in the percentages of “tone responded to first” trials between the

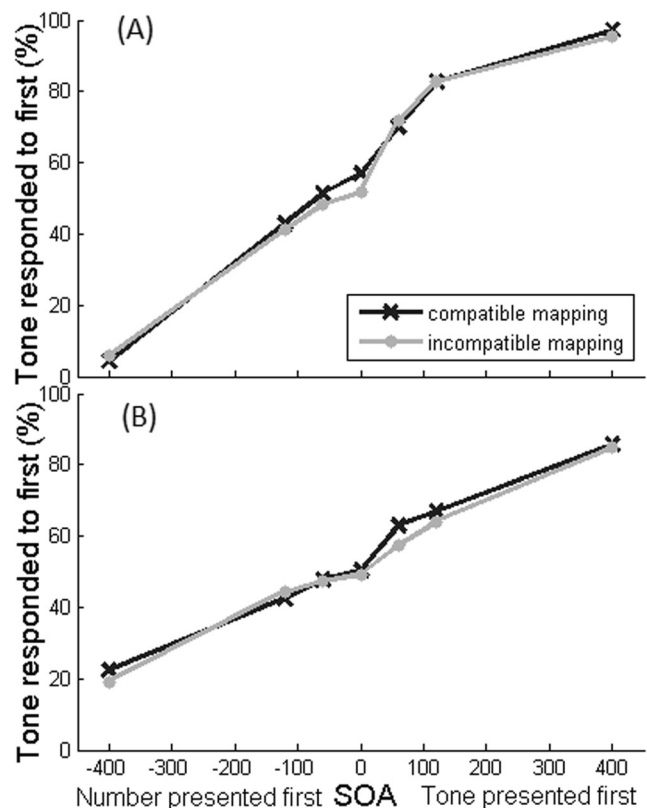


Fig. 5 Percentages of trials in Experiment 2 on which participants responded to the auditory task first for each condition (strong/weak contrast) and stimulus onset asynchrony (SOA). (A) Order instructions. (B) Free-choice instructions.

(compatible and incompatible) mapping conditions, $F(1, 37) = 1.059, p = .31$ —consistent with the prediction that the compatibility manipulation would impact the response order. As expected, SOA did have an effect on the percentage of “tone responded to first” trials, $F(3.09, 114.28) = 142.591, p < .01$, which was moderated by instructions, $F(6, 222) = 7.369, p < .01$. Follow-up t tests showed that the number of response reversals was higher with the free-choice than with the order instructions for the following SOAs: -400 ms, $t(19.67) = -3.139, p < .01$; 120 ms, $t(37) = 3.778, p < .01$; and 400 ms, $t(17.72) = 4.235, p < .01$. This pattern indicates that, under the free-choice instruction, participants tended to operate a more relaxed control of task order at the extreme SOAs. This tendency was, however, independent of the difficulty of response selection [Instruction \times SOA \times Mapping interaction: $F(6, 222) < 1$ —that is, task performance was not affected by the difficulty of the central processing stage. No other main effects or interactions were significant.

RTs

RTs were examined by mixed-measures ANOVAs with Mapping (compatible vs. incompatible) and SOA ($0, -60, -120, -400$ ms) as within-subjects factors and

Instructions (order vs. free-choice) as a between-subjects factor (Figs. 6 and 7).

VPRF trials

RT1 (visual task) The manipulation of the stimulus–response mapping had a significant effect on RT1, $F(1, 34) = 53.411, p < .01$, which was prolonged overall with an incompatible as compared to a compatible mapping (1,393 vs. 1,182 ms). Furthermore, RT1 differed between the two instruction conditions: Participants required more time to respond in the order than in the free-choice condition (1,418 vs. 1,156 ms), $F(1, 34) = 6.021, p < .05$. The only additional effect was the three-way interaction of mapping, SOA, and instruction, $F(3, 102) = 5.725, p < .01$. To examine this interaction in more detail, the RT1 data were analyzed separately for the two instruction conditions. With the order instructions, RT1 was significantly slower when the stimulus–response mapping was incompatible (vs. compatible) for all but the -120 -ms SOA [interaction of mapping and SOA: $F(3, 54) = 3.765, p < .05$; SOA = 0 ms: $t(18) = -3.602, p < .01$; SOA = -60 ms: $t(18) = -4.937, p < .01$; SOA = -120 ms: $t(18) = -1.554, p > .14$; SOA = -400 ms: $t(18) = -5.527, p < .01$]. The Mapping \times SOA interaction was also significant with the free-choice instructions, $F(3, 48) = 3.217, p < .05$. Whereas RT1 was unaffected by SOA in the

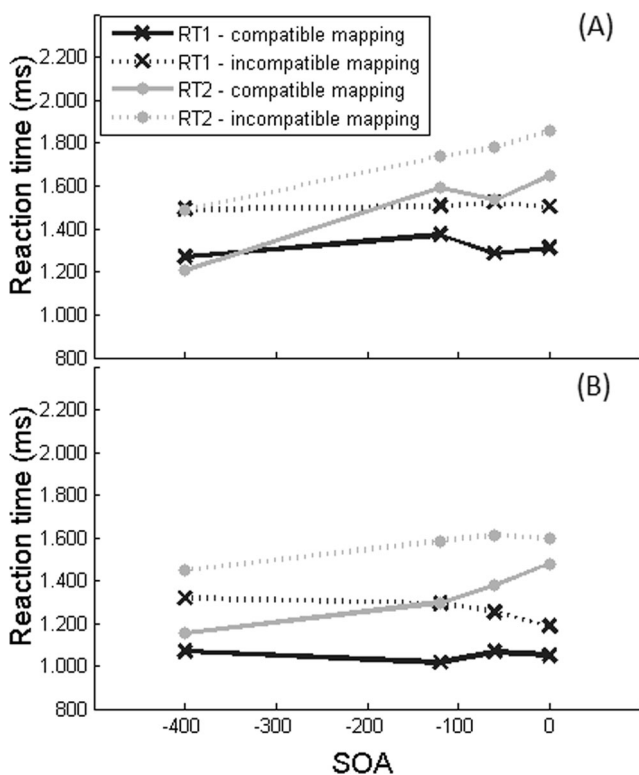


Fig. 6 Reaction times to the visual and auditory tasks for the trials in which the visual task was presented first and responded to first at different levels of stimulus onset asynchrony (SOA) in Experiment 2. (A) Order instructions. (B) Free-choice instructions.

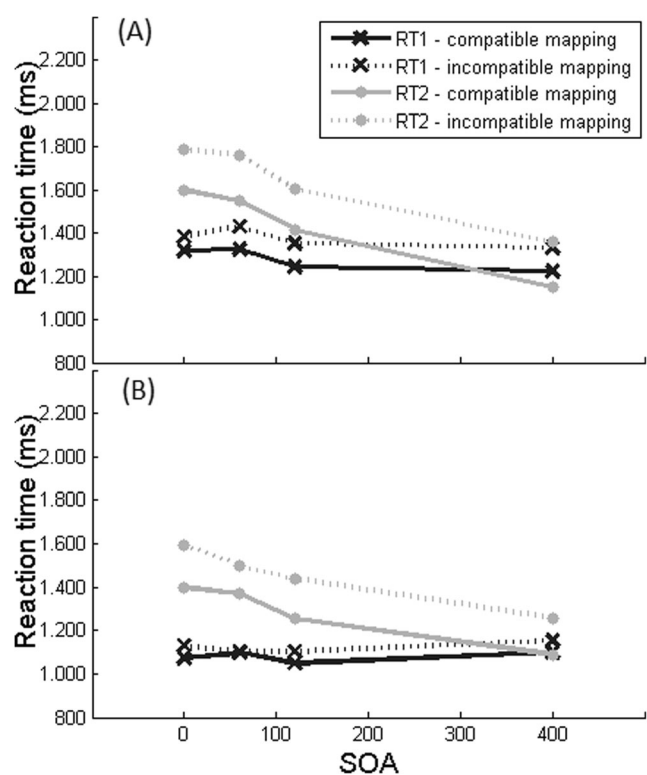


Fig. 7 Reaction times to the visual and auditory tasks for the trials in which the auditory task was presented first and responded to first at different levels of stimulus onset asynchrony (SOA) in Experiment 2. (A) Order instructions. (B) Free-choice instructions.

compatible condition, it become slower with increasing SOA in the incompatible condition: RT1 was significantly shorter at SOA 0 (1,186 ms) than at the of SOAs of -400 ms (1,318 ms), $t(16) = 3.413$, $p < .01$, and -120 ms (1,292 ms), $t(16) = 2.309$, $p < .05$; this slowing of RT1 with increasing SOA is likely to reflect response grouping under the specific conditions of an incompatible mapping (e.g., Miller & Ulrich, 2008). In the present case, participants showed grouped responses with an interresponse interval of < 100 ms in 3.2% of the trials.

RT2 (auditory task)

According to the bottleneck model, prolongation of the first-presented visual task should also increase RT2, since the (second-presented) auditory task would have to wait for processing at the bottleneck. In fact, mapping did indeed have a significant effect on RT2, $F(1, 34) = 67.055$, $p < .01$, which was longer in the incompatible than in the compatible condition (1,651 vs. 1,412 ms). Similar to RT1, RT2 was significantly longer with the order than with the free-choice instructions (1,625 vs. 1,444 ms), $F(1, 34) = 67.055$, $p < .01$. As is predicted by the central bottleneck model, the (main) effect of SOA was significant, $F(3, 102) = 55.616$, $p < .01$, reflecting the typical PRP effect. The SOA effect interacted with instructions, $F(3, 102) = 5.383$, $p < .01$ (i.e., the PRP effect was more marked in the order than in the free-choice condition) as well as with mapping, $F(3, 102) = 3.051$, $p < .05$ (i.e., the PRP effect was reduced in the incompatible as compared to the compatible condition, possibly resulting from the more marked effect of Task 1 processing in the former than in the latter condition, particularly at long SOAs). The Mapping \times SOA \times Instructions interaction was also significant, $F(3, 102) = 5.044$, $p < .01$. With the order instructions, RT2 was significantly longer in the incompatible than in the compatible condition for each SOA, except that of -120 ms [SOA = 0 ms, $t(18) = -3.677$, $p < .01$; SOA = -60 ms, $t(18) = -5.233$, $p < .01$; SOA = -120 ms, $t(18) = -1.598$, $p = .13$; SOA = -400 ms, $t(18) = -6.732$, $p < .01$], which parallels the pattern evident for RT1. In contrast, with the free-choice instructions, RT2 was significantly longer in the incompatible condition for each SOA, except for a marginal difference at the 0-ms SOA [SOA = 0 ms, $t(16) = -2.056$, $p = .06$; SOA = -60 ms, $t(16) = -5.256$, $p < .01$; SOA = -120 ms, $t(16) = -6.136$, $p < .01$; SOA = -400 ms, $t(16) = -8.258$, $p < .01$].

APRF trials

RT1 (auditory task) The RT1 analysis revealed an effect of mapping (i.e., the mapping in the visual task), $F(1, 36) = 13.424$, $p < .01$: RT1 was longer in the incompatible than in the compatible condition (1,245 vs. 1,176 ms). Although this result is not predicted by the traditional bottleneck model, it has been reported in other studies (e.g., Duncan, 1979) and

can be reconciled with bottleneck assumptions by assuming an influence of the difficulty of the visual task on general task preparation and a limited capacity to prepare for multiple stimulus–response mappings (Schubert, 1999; Strobach, Salminen, Karbach, & Schubert, 2014). Instructions also had a significant effect on RT1, $F(1, 36) = 6.175$, $p < .05$, which was longer with the order than with the free-choice instructions (1,320 vs. 1,100 ms). No other (main or interactions) effects were significant.

RT2 (visual task) For RT2, a significant effect of mapping was revealed, $F(1, 36) = 60.741$, $p < .01$: RT2 was longer in the incompatible than in the compatible condition (1,525 vs. 1,347 ms). In line with that predictions of the central bottleneck model, SOA also yielded a main effect, $F(3, 108) = 82.319$, $p < .01$: RT2 increased with decreasing SOA (i.e., a PRP effect). Although the effect of instructions did not reach significance, RT2 was again (numerically) longer with the order than with the free-choice instructions (1,508 vs. 1,363 ms), $F(1, 36) = 2.555$, $p = .12$. No interactions—particularly those involving mapping—were significant, providing evidence for the additive effect of the stimulus–response compatibility manipulation with SOA.

Error rates

The error rates were examined in an ANOVA with Task (auditory task vs. visual task), Mapping, and SOA (0, -60 , -120 , -400 ms) as within-subjects factors and Instructions as a between-subjects factor (Table 1). The results revealed error rates to be higher in the incompatible than in the compatible condition (8.8% vs. 6.9%), $F(1, 37) = 5.619$, $p < .05$. A significant Task \times Mapping interaction, $F(1, 37) = 20.752$, $p < .01$, was moderated by instructions, $F(1, 37) = 5.992$, $p < .05$. With the order instructions, the error rates for the visual task were increased in trials with the incompatible as compared to the compatible mapping (11.5% vs. 4.3%), $t(21) = -3.697$, $p < .01$; for the auditory task, by contrast, the error rates were lower in trials with an incompatible mapping (7.2% vs. 10.9%), $t(21) = 2.084$, $p < .05$. This pattern may reflect participants paying more attention to the auditory task when they experienced the visual task as being (too) difficult. With the free-choice instructions, the error rates differed between the two mapping conditions only for the visual task, not for the auditory task, suggesting that such an attention effect on the latter task was not present under the free-choice instruction condition. For the visual task, the error rate was increased for the incompatible versus the compatible mapping (8.3% vs. 4.4%), $t(16) = -7.204$, $p < .01$, simply showing that the compatible condition was the easier condition. The Task \times SOA interaction was also significant, $F(6, 222) = 3.521$, $p < .01$: Participants made more errors in the auditory than in the visual task, but only on trials in which the visual task was

presented first [error rates differed between tasks at the SOAs of -400 ms, $t(38) = -2.641$, $p < .05$, and -120 ms, $t(38) = -2.303$, $p < .05$]. This data pattern is similar to the results of Experiment 1: Tone information might have decayed when the auditory task was Task 2 and so was presented during processing of the visual task. Such decay was not present when the auditory task was Task 1. No other effects were significant.

Discussion

In line with the prediction deriving from the arrival time “first-come, first-served” principle, Experiment 2 showed that manipulating the central bottleneck stage did not lead to an increase in response reversals, whatever the instructions (order or free-choice). As in Experiment 1, the instruction manipulation led to an increased incidence of reversals in the free-choice as compared to the order condition, particularly at long SOAs—reflecting a general tendency to rely less stringently on stimulus order in the free-choice condition. The fact that the increase in response reversals at long SOAs was not modulated by the stimulus–response mapping (compatible vs. incompatible) supports the assumption that the point in time at which access to the bottleneck was determined was unaffected by the difficulty of response selection, whatever the instructions. Furthermore, it shows that this time point is situated before the central stages in both instruction conditions (recall that, as for response reversals, response selection difficulty did not interact with instructions). Similar to Experiment 1, RTs were increased overall with the order instructions, pointing to the involvement of additional control processes in this condition.

Moreover, the RT results are largely in line with a bottleneck model that assumes serial processing of the central (i.e., response selection) stages in the two tasks (Pashler, 1994). However, differential RT patterns emerged between the two instruction conditions. First, under the order instructions, on VPRF trials, RT1 (visual task) was increased at the 120-ms SOA in the compatible condition, and this increase in RT1s was propagated onto RT2s (auditory task)—a pattern that was not evident with the free-choice instructions. Possibly this finding (which was unexpected according to the central bottleneck model) is attributable to “input interference” (Hein & Schubert, 2004): The onset of a salient stimulus in Task 2 (e.g., a strong-contrast stimulus) may draw attentional resources away from Task 1, prolonging the time required to process Task 1; due to the bottleneck mechanism, this additional processing time is propagated to RT2.

But why, then, did the tone only produce interference in the compatible-mapping condition? A possible answer is provided by Kornblum, Hasbroucq, and Osman’s (1990) dimensional overlap model. This model assumes that when the relevant stimulus and response dimensions are conceptually,

perceptually, or structurally similar, the stimulus will trigger two response subprocesses: automatic activation of the congruent response, and intentional identification of the assigned response (Lien & Proctor, 2002). If the automatically activated response turns out to be incorrect, as in the incompatible condition, it has to be inhibited, and the correct response has to be determined and selected. Accordingly, with the order instructions, the tone might have interfered only in the compatible, and not the incompatible, condition because, in the latter, active control processes of response inhibition and intentional response determination were required that might have prevented the disruption. The situation was quite different with the free-choice instructions, with which RT1 (visual task) deviated from the typical PRP effect in one further respect: In the incompatible condition, RT1 was shorter at the 0-ms SOA than at the longer SOAs. At the 0-ms SOA, the response order was approximately at chance level, suggesting that participants simply responded quickly in a random order, as was allowed under the free-choice instructions. The instruction to freely choose the response order may have given participants the opportunity to decide upon the order without considering any limiting criteria (such as stimulus order), which permitted faster responding (shorter RTs), particularly in the compatible condition.

Could this pattern of RT findings simply be explained with a model allowing strategic implementations of processing bottlenecks, and thus full parallel as well as sequential processing under different instruction conditions (e.g., EPIC; Meyer & Kieras, 1997)? If a strategic bottleneck is defined such that it can allow for either parallel or sequential processing under any conditions, with no predictive constraints on that flexibility, then that model may be difficult if not impossible to falsify and may possess no predictive power. In contrast, the central bottleneck model and its structural response selection bottleneck is strongly constrained in important respects and clearly excludes outcomes that were plausible a priori.

At this point, it is also essential to discuss the present (largely lacking) response reversal effects of the central stage manipulation on task order processing in the context of studies that have investigated this task order processing in PRP dual tasks with an auditory tone and a visual letter task. The time consumption of the central stage in the letter task has been manipulated by the presence (prolonged condition) or absence (short condition) of a requirement for mental rotation; these tasks were presented in a standard PRP design with constant task order (Leonhard et al., 2011) and with random stimulus order (Ruiz Fernández et al., 2011). In contrast to Sigman and Dehaene (2006), this central stage manipulation led to an increase in response reversals in the prolonged in contrast to the short condition at short SOAs. One potential explanation for this difference could be that Sigman and Dehaene (2006) employed order instructions, whereas Leonhard, Ruiz Fernández, and colleagues employed free-choice instructions instead (i.e., participants were told to respond as quickly and

accurately as possible to both tasks, emphasizing that both tasks were equally important). However, the present study provided no evidence consistent with this explanation, because we employed both order and free-choice instructions and were not able to show an effect of the central stage manipulation under either of these conditions. So, differences in task instructions might not explain the differences between these studies' findings.

Alternatively, the manipulations in the present study as well as in Sigman and Dehaene (2006) may not have sufficiently prolonged the central stage durations to motivate participants to prioritize the less time-consuming task; such a prioritization would be expected if participants strategically performed two component tasks with a minimal total reaction time (TRT; Miller et al., 2009). Although participants were able to detect Sigman and Dehaene's (2006) effect of 112 ms in the central stage manipulation (Corallo, Sackur, Dehaene, & Sigman, 2008), which was very similar in duration to the effect in the present study, the massive effect of short versus prolonged conditions by Ruiz Fernández et al. (2011) of 227 ms allowed participants to assess the task duration and central stage manipulations rather easily. As such, these participants were able to use the TRT strategy. The application of such a strategy might not be probable in the present study as well as in the study of Sigman and Dehaene (2006), which both included a smaller central stage manipulation effect. Thus, the conclusions from the present Experiment 2 might be relevant for dual-task situations that do not present the possibility of employing strategies incorporating minimizing TRTs. In contrast, the use of the TRT strategy to control task order is limited to contexts with a comparatively massive central stage effect, such as the one realized by Leonhard, Ruiz Fernández, and colleagues.

Findings from the present PSS analysis and the analysis of the steepness of the function (for the difference limen, DL) in Ruiz Fernández et al. (2011) showed a divergence. Whereas the present study showed no effect on the time point at which participants responded to the tone first on 50% of the trials (i.e., PSS), the DL analysis showed that participants tended to perform the less time-consuming tone task first more often in the dissimilar than in the similar condition. Hence, the latter results suggest that the duration of central processes influences the central processing order, whereas this was not the case in the present study. The reason for these differences in the conclusion between the PSS analysis and the DL analysis might again be the differences in the effects of the central stage manipulations, as outlined above.

General discussion

The present study was designed to examine whether dual-task processing order at the central bottleneck stage is determined

by the central arrival time “first-come, first-served” principle. To this end, we presented dual (visual and auditory) tasks with a varying task order and manipulated the duration of separable processing stages of a visual task. Prolonging the arrival time by manipulating the perceptual stage was expected to have an effect on response reversals, particularly when the visual task was presented first. Specifically, prolonging perceptual (stage) processing of the visual task would make the second-presented task (i.e., the auditory task) arrive earlier at the bottleneck, as a result of which the auditory task should be responded to first more often. By contrast, prolonging the response selection stage of the visual task should not lead to a change in the response order, because the respective (central stage) manipulation would not affect the arrival time of the visual task at the bottleneck.

The results indeed showed that response order is dependent on the central arrival times of the tasks, in line with the “first-come, first-served” principle: Prolonging the prebottleneck stage of the visual task through a stimulus–background contrast manipulation led to an increase in the percentage of trials in which the auditory task was responded to first (Exp. 1); in contrast, prolonging the response selection stage of the visual task had no effect on response order (Exp. 2). The results also show that the influence of arrival time on response order is independent of the specific instructions—order versus free-choice—given to the participants. In other words, this influence generalizes across dual-task situations and conditions, rather than being attributable to a particular strategy (artificially and unintentionally) induced by the order instructions.

Dual-task instructions and task order control

Although the two dual-task instructions exhibited many similar effects on response reversals, detailed analyses also revealed a number of differences between them. Across both experiments, participants generally produced more response reversals under the free-choice than under the order instruction at long SOAs. This was likely due to a generally stronger reliance of task control on stimulus order in the order condition—consistent with previous proposals that the order condition involves the recruitment of additional control processes (de Jong, 1995; Szameitat et al., 2006; Umiltà et al., 1992). Greater involvement of control processes would also explain the present observation that RTs were generally slower in the order than in the free-choice condition.

Furthermore, RTs in dual-task trials with the auditory task presented first showed an impact of stimulus contrast under the order but not the free-choice instructions. This is consistent with the view that order instructions especially direct participants' attention to stimulus order in their decisions about task order. Stronger perceptual contrast of the visual stimulus may expedite the decision under the order condition—explaining the selective contrast effect in the order (but not the free-

choice) condition. Given these arguments, our RT data show that findings from dual-task studies with order instructions, such as in Sigman and Dehaene (2006), do not entirely generalize to other task conditions.

Interestingly, in the free-choice condition, even though participants could respond in any order they preferred, task order (as revealed by response order) was also mostly dependent on the actual order in which the tasks (stimuli) were presented. This is likely indicative of a default setting of the processing system to process the task in line with the stimulus order. More specifically, although de Jong's (1995) and Luria and Meiran's (2003) studies showed that participants can prepare ad hoc for a certain (pre-cued) task order, it is more plausible that participants normally avoid deciding upon the task order anew on each trial; instead, they keep looking for consistent cues informing an order decision—and one readily available cue is the presentation order of the stimuli. Also, the fact that participants were asked to respond as fast and as accurately as possible might have reinforced their tendency to rely on the order of task (stimulus) presentation.

From a different perspective, these findings across the different instruction conditions are consistent with strategic and structural bottleneck models with a potential capacity limitation at the central response selection stage (e.g., Meyer & Kieras, 1997; Pashler, 1994); whereas the former type of models assume the instantiation of bottleneck processing due to strategic reasons (with the alternative strategy of parallel processing), the latter assume unavoidable capacity limitations. As a consequence, the present experiments were not conclusively diagnostic for both model types, and we leave the answer to this issue to future studies using different instruction conditions.

Arrival time in the context of alternative determinants of processing order

As regards the factors determining task processing order, the present study was designed to re-investigate Sigman and Dehaene's (2006) central arrival time account, while aiming to provide more conclusive evidence for this account than the predecessor study. Overall, our findings are consistent with, and in fact add important new evidence (based on PSS analyses) to this account, in particular: the fact that the stimulus contrast manipulation significantly affected the PSS, whereas the response mapping manipulation did not, may be taken to indicate that the former manipulation is located at a pre-bottleneck and the latter at a bottleneck stage. Based on the finding that the contrast manipulation affected the PSS, we can even determine the point in time at which the output of the perceptual (stimulus identification) stage is granted access to central bottleneck stage: the PSS in our study denotes the point in time at which the visual stimulus was perceived as simultaneous with the auditory stimulus. Note that the visual-

auditory PSS is commonly assumed to reflect differences in the internal stimulus processing time between the auditory and the visual modality, rather than reflecting the physical presentation times of the stimuli (Shi et al., 2010).

Although the present findings are in accord with the central arrival time account, they do not fully rule out the possibility of alternative, or additional, determinants, such as the detection times of the stimuli (e.g., Leonhard & Ulrich, 2011) or participants' expectations (e.g., expectations based on task order in previous trials or cues indicating task order; de Jong, 1995; Luria & Meiran, 2003). One reason is that, although our stimulus contrast manipulation (targeted at the perceptual stimulus analysis stage) may have resulted in differences in arrival times, it also may have influenced stimulus preprocessing (e.g., Boenke et al., 2009; Miller & Schwarz, 2006; Sternberg & Knoll, 1973)—that is, the start of perceptual processing proper (i.e., stimulus detection times).

In this regard, the findings of a study by Leonhard and Ulrich (2011) are somewhat puzzling, and thus worth discussing in more detail. Leonhard and Ulrich used a PRP paradigm with a visual and an auditory discrimination task, which were presented in varying orders. In the visual task, participants discriminated between a plus and a minus sign, which were presented under either intact or degraded visual conditions—where the latter was assumed to result in delayed stimulus detection relative to the former. Degradation of the visual stimulus was realized by overlaying the plus or minus sign with a large and complex pattern of randomly distributed masking squares. For the conditions with two tasks presented in variable order, Leonhard and Ulrich predicted a significant interaction of visual stimulus degradation and task order (visual–auditory or auditory–visual) on the percentage of response reversals: For trials with visual–auditory task order, the percentage of response reversals was expected to *increase* when the visual stimulus was degraded as compared to when it was intact, but not for trials with auditory–visual order.

Importantly, Leonhard and Ulrich (2011) found that for the visual–auditory trials, the percentage of response reversals was *lower* (rather than higher, as predicted on the central arrival time assumption) when the visual stimulus was degraded rather than intact. Although this particular finding might appear to challenge the validity of the central arrival time assumption (supported by the present and other findings), some special factors might have caused this decrease in response reversals under degraded stimulus conditions in that study. For example, Leonhard and Ulrich's procedure to manipulate “stimulus contrast” by presenting a complex mask in the degraded condition, but no mask in the intact, condition may actually have increased the overall perceptual saliency of the stimulus in the degraded relative to the intact condition (with a far smaller and less salient stimulus). This may have reduced the detection time for the stimulus in the degraded condition and affected participants' task order strategy by inducing a preference for

the degraded but visually more complex stimulus (over the intact stimulus). Given this, the finding of fewer response reversals in this (as compared to the intact) condition may not necessarily argue against the validity of central arrival time assumption. In any case, Leonhard and Ulrich's findings do not contradict the notion that the processing stream of the task that reaches the central processing stage first enters the bottleneck first. As such, the precise timing and location of the task manipulations by Leonhard and Ulrich is not entirely clear to come to conclusive conclusions about task order processes and their location in relation to component task processing stages.

Nevertheless, one argument against the effects of the present contrast manipulation (i.e., varying stimulus contrast on a constant background) could be that this manipulation results in differences in the central arrival time exclusively because of differences in the time to detect the varying stimuli as supported by Leonhard and Ulrich (2011). To rule out this explanation, we run an additional single-task control experiment, in which stimulus contrast was the critical stimulus dimension. In this control, we presented the visual stimuli “2,” “5,” and “9” as in the main experiments, across three blocks with 60 trials per block, and we manipulated the stimulus contrast at the two levels of the manipulation in the present Experiment 1 (i.e., high vs. low contrast). Importantly, participants were instructed to manually respond to stimulus contrast in a detection task; in other words, participants should indicate by responding with different fingers whether a stimulus was presented with high contrast or with low contrast. By this task we aimed to enforce subjects to make a decision, which is purely based on the difference in brightness of the two types of stimuli; the difference would reflect the time for detecting the high versus low contrast stimulus. If this difference is smaller than the difference in the task conditions of Experiment 1, in which participants were required to distinguish between different number and therefore to identify the stimuli, then the results of Experiment 1 could not be explained solely by differences in the detection time; in that case, we would infer for an additional contribution of differences in the central arrival time due to the larger differences in stimulus identification than in stimulus detection. As a result, RT analysis of the data of 13 participants (as in Exp. 1, we excluded RTs outside three *SDs* from the individual condition means) demonstrated faster RTs under the high-contrast condition ($M = 448$ ms) in comparison to the low-contrast condition ($M = 484$ ms). This difference was compared with the RT difference between a low contrast and high contrast condition in a previous pilot experiment, when participants responded to the identity of the visual stimuli in an identification task. In this identification task, fifteen participants also produced faster RTs under the high contrast condition ($M = 534$ ms) in comparison to the low contrast condition ($M = 627$ ms). The comparison was realized in a mixed-measures ANOVA with the within-subjects factor

Contrast (high vs. low) and the between-subjects factor Task (contrast task [control experiment] vs. identification task [pilot experiment]). The main effects of contrast, $F(1, 26) = 39.170$, $p < .001$, and task, $F(1, 26) = 11.451$, $p < .01$, were significant; RTs were generally lower under the high contrast in comparison to the low contrast condition as well as in the contrast task in comparison to the identification task. Importantly, the interaction was significant, $F(1, 26) = 7.566$, $p < .05$, reflecting the fact of a larger contrast effect in the contrast task (control experiment) than in the identification task (pilot experiment). Thus, although the difference in the contrast task of $M = 36$ ms was significant, $t(12) = 2.31$, $p < .05$, this difference was significantly lower than the difference of $M = 93$ ms between the low-contrast and high-contrast condition in the identification task, $t(12) = 3.63$, $p < .01$. Consequently, our single-task control experiment and its comparison to the previous pilot work demonstrated that perhaps only a minor part of the differences in central arrival time can be attributed to detection time in the visual task with stimulus identification. Thus, we assume that the present manipulation of stimulus contrast in the identification task is not fully predicted by differences in detection time and that differences in central arrival time contributed to the observations in Experiment 1.

Whatever the precise account, future studies will be necessary to disentangle potential interactions of detection time and arrival time on processing order. This issue gains additional importance if it is considered in combination with (intertrial-induced) expectancies or (cue-induced) order preparation when identifying the factors that determine the order of task processing. Another open issue for future studies concerns manipulations designed to target detection time, arrival time, TRT strategy (e.g., Leonhard et al., 2011) and/or expectation/preparation with regard to the (components of the) auditory task.

Summary

In summary, our findings indicate that response order at the central bottleneck is influenced by the differential arrival times of the tasks at the bottleneck. Moreover, we could show that this effect is largely independent of the instructions (i.e., order vs. free choice) if we look at the general picture of task order in dual-task situations. However, a more fine-grained analysis of task scheduling at the levels of RTs and response reversals showed differences in task order control between the order instructions. Under free-choice conditions, a reduced reliance of task control on stimulus order was observed, whereas control processes are likely activated in the order instruction condition that make participants rely more consistently on the presentation order of the stimuli. The “first-come, first-served” principle operated to the same degree under both instruction conditions when the task order followed the stimulus presentation order.

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