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Distorted subjective reports of stimulus onsets under dual-task conditions: Delayed conscious perception or estimation bias? ☆

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1. Introduction

It is widely agreed that attention and consciousness are highly related. The precise nature of the relationship, however, is still under debate. While some theorists view attention as a prerequisite for consciousness (e.g., Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006), others contend that attention is neither necessary (van Boxtel, Tsuchiya, & Koch, 2010) nor sufficient for consciousness (Kentridge, Nijboer, & Heywood, 2008). Consistent with the former view, several authors have put forward the notion that decision-making (e.g., response selection) and conscious access (via consolidation of a stimulus representation into short-term memory) are subject to the same central or attentional bottleneck (Arnell & Jolicoeur, 1999; Marti, Sigman, & Dehaene, 2012; Ruthruff & Pashler, 2001; Tombu et al., 2011). Accordingly, while perceptual and motor processing of one task can occur in parallel with the processing of another task, response selection and conscious access are strictly serial.

Such a unified attentional bottleneck has been proposed to account for two dual-task phenomena that were originally thought to arise from separate central and perceptual processing limitations: the psychological refractory period (PRP) effect and the attentional blink. The PRP effect arises when participants provide speeded responses to two stimuli that are presented with varying stimulus onset asynchronies (SOAs); responses for the second task slow down as the SOA decreases (e.g., Pashler, 1994). For the PRP effect, response selection is thought to be the critical bottleneck process; responses for Task

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2 are slowed at short SOAs because response selection for Task 2 is postponed until the response for Task 1 has been selected. The attentional blink occurs when participants are required to detect two targets in a stream of briefly presented visual stimuli; participants often fail to report Target 2 if it appears shortly after Target 1 even though they are not required to provide a speeded response to the targets as in the PRP paradigm (e.g., Raymond, Shapiro, & Arnell, 1992). For this effect, short-term consolidation is considered the critical bottleneck process; consolidation of Target 2 cannot take place as long as Target 1 is being consolidated. The sensory representation of Target 2 decays over time and can also be masked by another stimulus. If the sensory representation of Target 2 has completely faded or is disrupted before Target 1 has been consolidated, participants do not become aware of Target 2.

Evidence in support for the notion that the PRP effect and the attentional blink arise from the same attentional bottleneck comes from studies that combined the PRP and the attentional blink tasks. These studies found that the proportion of trials in which participants failed to report Target 2 was related to the speed of Task 1 processing (Jolicoeur, 1999; Ruthruff & Pashler, 2001), and that the encoding of a target delayed a subsequent speeded response (Jolicoeur & Dell'Acqua, 1999; Ruthruff & Pashler, 2001; Tombu et al., 2011). These results suggest that while response selection is ongoing, short-term consolidation cannot occur and vice versa (see Jolicoeur, 1999). That is, response selection of one task can block the conscious awareness of another stimulus. While in the attentional blink paradigm, the temporal dynamics of conscious access can be directly inferred from Target 2 detection rates, in a PRP paradigm it is less clear when participants gain conscious access to the second stimulus. If response selection of a speeded Task 1 delays conscious access to a second target in a combined PRP and attentional blink paradigm it is conceivable that in a standard PRP paradigm, conscious access to the second stimulus can also be delayed.

As participants always provide two responses in a standard PRP paradigm, and are therefore said to be 'aware' of both stimuli, an alternative methodology is required to assess any possible delay in their conscious perception of the second stimulus. To assess the subjective (conscious) timing of the two tasks in a PRP paradigm, two previous studies introduced the method of quantified introspection (Corallo, Sackur, Dehaene, & Sigman, 2008; Marti, Sackur, Sigman, & Dehaene, 2010). In each experimental trial, participants performed the PRP task and subsequently estimated their reaction times for the two tasks (RT1 and RT2) on a visual analogue scale. While objective RT2 showed the typical PRP effect, estimates of RT2 were independent of SOA. That is, even though responses to Task 2 were delayed at short SOAs, participants did not report this response slowing in their RT2 estimates. This result pattern could be interpreted as an underestimation of RT2 at short SOAs, caused by a delayed conscious perception of the second stimulus. Marti et al. (2010) extended this method and reconstructed the subjective phenomenology of a PRP trial based on several introspective reports. In addition to the estimates of RTs, they asked participants to estimate the temporal gap between the onsets of the two tasks (i.e., the SOA), and the interval between their Task 1 decision and Task 2 onset. SOA estimates showed underestimation of long SOAs and overestimation of short SOAs. Even at zero SOA, when the two stimuli were presented simultaneously, participants estimated the SOA to be about 250 ms. As one would expect, estimates of the interval between Task 1 decision and Task 2 onset decreased with increasing task overlap. At very short SOAs, the Task 1 decision should occur much later than the Task 2 onset, and therefore this interval should be strongly negative. The estimates of this interval, however, did not differ from zero for the three shortest SOA conditions (ranging from 0 to 232 ms). Marti and colleagues interpreted these results as indicating that at short SOAs the conscious perception of the second stimulus is delayed until the end of Task 1 response selection.

The misperception of SOAs observed by Marti et al. (2010) is crucial to this interpretation. However, Corallo et al. (2008) observed a very similar misperception of SOAs in a control condition in which participants estimated the SOA without processing the two tasks. Thus, the distortions of the SOA estimates might be due to a general estimation bias rather than response selection of Task 1 delaying conscious awareness of Task 2. For example, these distortions might reflect a well-known bias in quantitative judgments called contraction bias or regression effect (i.e., the tendency for responses to gravitate toward a reference magnitude; Poulton, 1989). Accordingly, stimuli larger than the reference magnitude are underestimated and stimuli smaller than the reference magnitude are overestimated. Poulton noted that such a contraction bias is facilitated if the observer is provided with a limited range of responses with an obvious central value. To assess estimates of SOA, Marti et al. used a visual analogue scale with a range that corresponded to the range of possible objective SOAs (0–1000 ms). Thus, the consequence of participants avoiding the extremes of this scale would be an overestimation of short SOAs and an underestimation of long SOAs. Accordingly, the overestimation of short SOAs found by Marti et al. could reflect a methodological artefact induced by the limited response range of the visual analogue scales rather than delayed conscious perception of Task 2.

In the present study, we investigated whether response selection for Task 1 causes a delay in the conscious perception of the second stimulus in a standard PRP task (delayed conscious perception hypothesis). To assess the moments of conscious access in the PRP task more directly, we employed a widely used method of timing subjective events, that is, the clock paradigm—sometimes also referred to as rotating spot method (e.g., Libet, Gleason, Wright, & Pearl, 1983; Miller, Vieweg, Kruize, & McLea, 2010; Pockett & Miller, 2007). In this paradigm, a clock hand moves around a clock face on the screen while participants perform another task. At the end of each trial, participants are asked to indicate the position of the clock hand when a certain internal (e.g., Haggard & Cole, 2007; Pockett & Miller, 2007) or external (e.g., Joordens, van Duijn, & Spalek, 2002; Seifried, Ulrich, Bausenhart, Rolke, & Osman, 2010) event occurred. For the present purpose, the clock method offers two potential advantages over the use of visual analogue scales. First, in contrast to visual analogue scales which assess the temporal relationship between two points in time (e.g., the interval between the perceived onsets of the two stimuli), the clock method allows us to assess the specific points in time when participants perceived the stimulus onsets. Second,

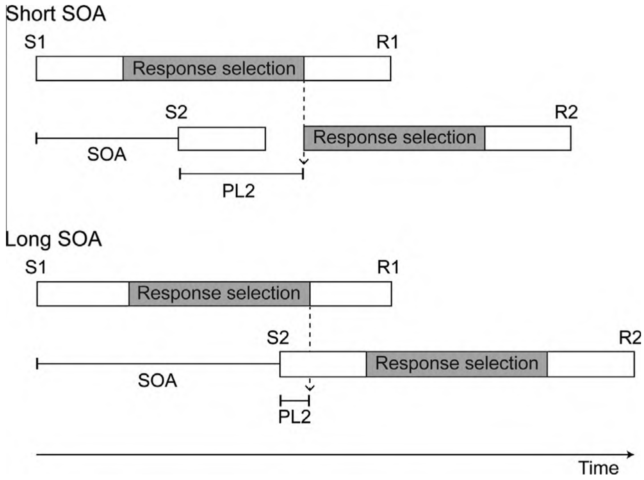

Fig. 1. Illustration of the delayed conscious perception hypothesis, at short and long SOAs. When S2 is presented during response selection for Task 1, participants do not become aware of S2 until the end of Task 1 response selection. The perceptual latency of S2 (PL2) is the deviation of the reported S2 onset from the objective S2 onset.

the clock method should be less prone to a possible contraction bias because the range of the clock is less restricted than the range of visual analogue scales. That is, while both scales are limited at the lower end (left end of the visual analogue scale and starting position of the clock) the upper end is unlimited for the clock.

According to the delayed conscious perception hypothesis, when the two tasks overlap, Task 2 cannot be consciously perceived until Task 1 response selection is complete (see Fig. 1). Thus, at short SOAs the onset of the second stimulus (S2) should be reported at a later position than its objective position. In contrast, when the two tasks do not overlap the conscious perception of Task 2 should be unaffected by Task 1 response selection. Thus, at long SOAs the onset of S2 should be reported at a position close to its objective position. Therefore, we focus on a *perceptual latency* (PL) measure, which is the deviation of the reported clock hand position from the objective position of stimulus onset. Perceptual latency for S2 onset (PL2) should be prolonged at short SOAs and should become shorter with increasing SOA.[1] In contrast, perceptual latency for S1 onset (PL1) should be short and constant across SOAs.

Another set of predictions can be derived with respect to trial-by-trial correlations between RTs and PLs. Most importantly, when the two tasks overlap, the longer it takes for a response to be selected for Task 1, the later S2 should be consciously perceived. Therefore, at short SOAs, RT1 and PL2 should be positively correlated and this correlation should become weaker with increasing SOA. Since RT1 and RT2 are usually correlated at short SOAs (because of the queuing of the two response selection stages) a similar pattern is expected for the correlation between RT2 and PL2. However, PL2 should exhibit a stronger relationship with RT1 than with RT2. For Task 1, PL1 might be weakly related to RT1 at all SOAs because variations in the detection time of S1 may be reflected in RT1.

2. Experiment 1

Experiment 1 employed an auditory S1 and a visual S2 in the clock paradigm. To ensure that participants focused their spatial attention on the clock hand's position at the time of S2 presentation, a transient color change of the clock hand served as S2. One group of participants was asked to provide separate speeded responses to the two stimuli (PRP group), whereas a control group only perceived the stimuli. The control group was included to test whether potential SOA effects on PLs in the PRP task are specific to the response requirements of the PRP task. In both groups, participants indicated the position on the clock face when they had perceived the onsets of S1 and S2 in each trial; PLs were calculated as the difference between the objective stimulus onsets and the reported stimulus onsets.

2.1. Method

2.1.1. Participants

In the PRP group, there were 5 males and 15 females, aged between 19 and 47 years ($M = 22.9$ years). The control group consisted of 3 males and 17 females, aged between 18 and 34 years ($M = 23.3$ years). All participants reported normal hearing and normal or corrected-to-normal vision, and received either course credit or payment.

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[1] At very short SOAs, if S2 is presented before response selection of Task 1 starts, the predictions with regards to PL2 are less clear. It is conceivable that in this situation, S2 can be consciously perceived without any delay due to Task 1 response selection. Thus, PL2 should be comparable to the PL2 at long SOA when the two tasks do not overlap. However, the findings of previous introspective PRP studies (Corallo et al., 2008; Marti et al., 2010) suggest that this is not the case, as iRT2 was constant across all SOAs even when the two stimuli were presented at the same time.

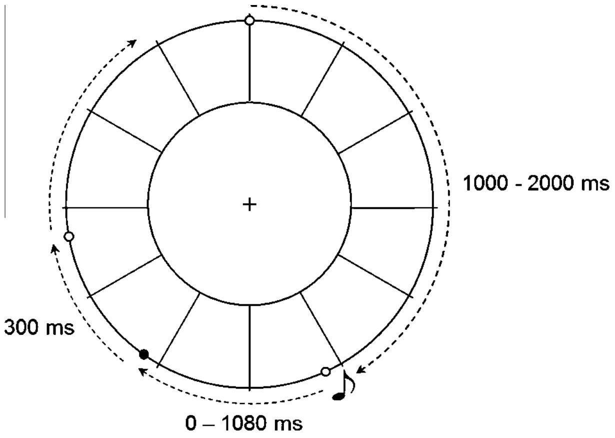

Fig. 2. Clock face with clock hand (the white circle) used for timing stimulus onsets. In each trial, the clock hand first rotated for a random foreperiod between 1000 and 2000 ms. Then a low or high tone (S1) was presented for 80 ms. After a variable stimulus onset asynchrony (0, 40, 120, 360 or 1080 ms), the color of the clock hand changed from white to red or blue for 300 ms (S2).

2.1.2. Apparatus and stimuli

The experiment was run in a sound-attenuated, dimly illuminated room. The experiment was programmed in Matlab© using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997) version 3.0.8. Two external response panels were used to record responses with the index and the middle finger of the left and right hand. The clock (see Fig. 2) was presented at the center of a computer screen (20 in., 150 Hz refresh rate, 1024 × 768 pixels) at a viewing distance of approximately 50 cm in black on a white background. The clock face was an unfilled circle with a diameter of 8.7° of visual angle and marked with ticks every 30° of the circle. A white dot with a diameter of 0.02° was employed as the clock hand and a cross of the size 0.03° marked the center of the clock. The clock hand moved in clockwise direction and revolved with a period of 2400 ms. S1 was a tone of either 440 or 880 Hz, presented via headphones (60 db SPL, 80 ms duration). S2 was a change of the clock hand's color from white to either blue or red for 300 ms.

2.1.3. Procedure and design

In the PRP task, each trial started with the presentation of the clock face, the cross, and the clock hand at the 12 o'clock position. Participants initiated the rotation of the clock hand with a key press. After the clock hand rotated for a random foreperiod between 1000 and 2000 ms, S1 was presented. S2 presentation followed S1 onset according to a variable SOA (0, 40, 120, 360, or 1080 ms). The clock face remained on the screen until the participant had provided all responses. As in the two previous studies (Corallo et al., 2008; Marti et al., 2010), participants were instructed to respond quickly and accurately to each stimulus as soon as it appeared. In Task 1, participants had to respond with their left middle finger to the low tone and with their left index finger to the high tone. In Task 2, they had to respond with their right index finger when the clock hand turned blue and with their right middle finger when the clock hand turned red. After an additional 500 ms, the clock face was presented again with a filled black clock hand at the 12 o'clock position. In case of an erroneous response in one of the two RT tasks, this screen also presented a feedback message indicating in which task an error had occurred. Participants then first reported the position of the clock hand when the tone had appeared and second when the clock hand had changed its color. In order to indicate the two positions, participants moved the clock hand around the clock using the response keys. After participants confirmed the first estimate with a press of the enter key on the computer keyboard, a new clock hand appeared for the second estimate while the first estimate remained on the screen.

In the control task, the trials of the PRP group were replayed to a new group of participants. Each participant experienced the trials of one corresponding participant of the PRP group. That is, the same foreperiods, SOAs and total trial lengths (determined by the second response of the corresponding participant in the PRP group) were used to create the trials presented to the control participant. The two stimuli, S1 (440 or 880 Hz) and S2 (color change of the clock hand to red or blue), were newly selected for each trial in a random way. The original participant's responses were not presented during the trial and control participants were naive to the task requirements of the PRP task. They were instructed to watch the clock and, at the end of each trial, to report the positions of the clock hand when they had perceived the onsets of S1 and S2. Assessment of the estimates was identical to the PRP group.

In both groups, participants performed one practice block (of dual-task trials) and ten experimental blocks. Each block consisted of four trials at each SOA level, that is, 20 trials in total. The experimental session lasted about 1 h.[2]

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[2] Participants of the PRP group also took part in another session in which they provided estimates for their decision time. The order of the two sessions was counterbalanced across participants. As there was no effect of session order on any of our dependent measures (*p*-values all over .2), and decision time data did not contribute to the theoretical issues considered, these results are not reported here.

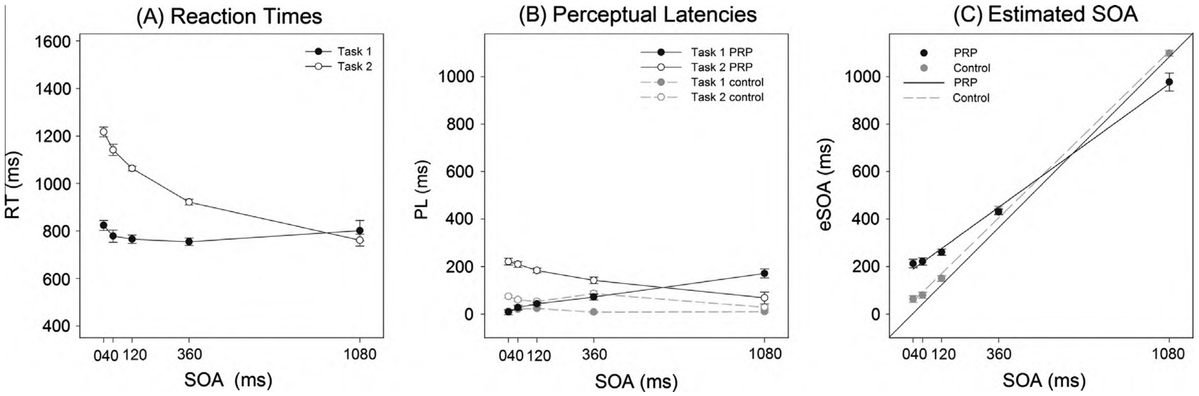

Fig. 3. RTs (panel A) in Task 1 and Task 2 as a function of SOA in the PRP group, and PLs (panel B) in Task 1 and Task 2 as a function of SOA and group (PRP vs. control) in Experiment 1. Panel C depicts eSOA (i.e., the interval between the estimates of S1 and S2 onsets) as a function of SOA and group; the lines represent the regression lines, and the identity line is shown for the purpose of comparison. Error bars represent ±1 within-subjects SE.

2.2. Results

2.2.1. Data analysis

For the PRP data, we discarded all trials from analyses that included an error in Task 1 and/or Task 2 (17.7%). Additionally, we discarded trials with RT1 or RT2 deviating more than three standard deviations from the individual mean in each SOA condition (2.9% of correct trials) and trials with implausible PLs (i.e., estimates that deviated more than 1000 ms from the objective stimulus onset; 1.6% of the remaining trials). For the control data, we discarded the same trials as in the PRP data with respect to errors and RT outliers. Additionally, we also discarded trials with implausible PLs (3.4% of the remaining trials) as in the PRP group. Reaction times (RT1 and RT2) from the PRP group were analyzed with ANOVAs including the within-subjects factor SOA (0, 40, 120, 360, or 1080 ms). We performed further ANOVAs for perceptual latency in Task 1 and Task 2 (PL1 and PL2); an overall ANOVA with the factor SOA and the between-subjects factor group (PRP vs. control), and separate ANOVAs for the PRP and the control group including only the factor SOA were conducted. We also analyzed the interval between the estimated S1 and S2 onsets (eSOA) with an ANOVA including the factors SOA and group. The Greenhouse-Geisser correction was used to adjust p-values where appropriate. Standard errors were calculated according to Cousineau (2005). Correlation analyses on the PRP group data followed the procedure of Marti et al. (2010). Accordingly, Pearson product–moment correlations were calculated within each participant and SOA. Separate one sample t-tests were then performed on the correlation coefficients for each SOA to test whether they differed from zero. Additional ANOVAs were performed to test whether the correlations differed across SOAs.

2.2.2. Reaction times

Fig. 3A shows RT1 and RT2 as a function of SOA in the PRP group. The slight increase of RT1 at short SOAs was not significant, $F(4,76) = 0.87$, $p = .407$, $\eta_p^2 = .04$, and Task 2 performance showed the standard PRP effect (the difference in RT2 between the longest and shortest SOA was 451 ms), $F(4,76) = 71.70$, $p < .001$, $\eta_p^2 = .79$. Thus, RT results showed the standard pattern observed in the PRP paradigm suggesting that implementing the PRP task in the clock paradigm does not qualitatively alter task performance.

2.2.3. Perceptual latencies

Fig. 3B depicts PL1 and PL2 as a function of SOA and group. The results showed a clear difference between the two groups for PL1 and PL2. The overall ANOVA on PL1 revealed a marginally significant effect of group, $F(1,38) = 3.49$, $p = .070$, $\eta_p^2 = .08$, and a significant interaction of group and SOA, $F(4,152) = 22.46$, $p < .001$, $\eta_p^2 = .37$. In contrast to our expectations, in the PRP group PL1 linearly increased from the zero SOA (8 ms) to the longest SOA (171 ms), $F(4,76) = 22.51$, $p < .001$, $\eta_p^2 = .54$. In the control group, no such linear increase was observed. Instead, there were slightly longer PL1s at the 40 ms (21 ms) and 120 ms SOAs (24 ms) in comparison to the longest SOA (11 ms). Nevertheless, the effect of SOA on PL1 was also marginally significant in this group, $F(4,76) = 2.56$, $p = .061$, $\eta_p^2 = .12$.

The overall ANOVA on PL2 revealed a significant effect of group, $F(1,38) = 15.29$, $p < .001$, $\eta_p^2 = .29$, and a significant interaction of group and SOA, $F(4,152) = 6.96$, $p = .002$, $\eta_p^2 = .15$. In the PRP group, PL2 was affected by SOA, $F(4,76) = 12.21$, $p < .001$, $\eta_p^2 = .39$. PL2 was longest at the zero SOA (221 ms) and linearly decreased with SOA (68 ms at the longest SOA). In the control group, PL2 also showed a decrease with increasing SOA, $F(4,76) = 5.84$, $p = .007$, $\eta_p^2 = .24$. However, this decrease was not as linear as in the PRP group and much smaller. PL2 was only slightly longer at the zero SOA (74 ms) than at the longest SOA (29 ms), and was longest at the 360 ms SOA (86 ms).

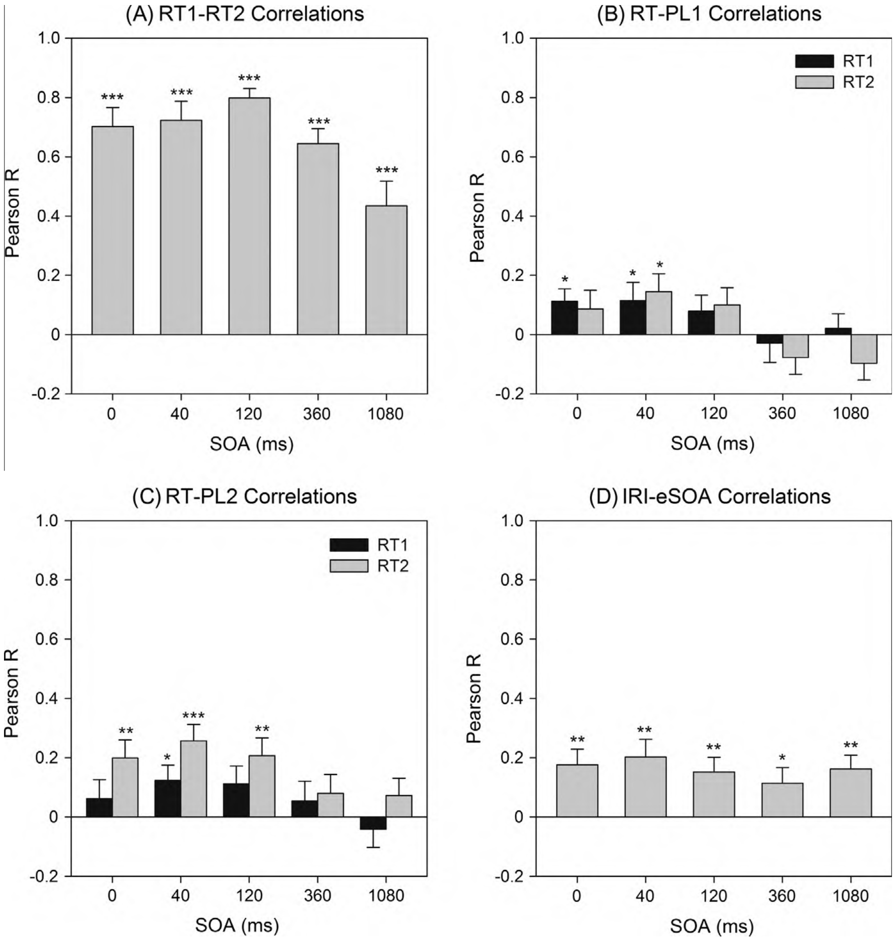

Fig. 4. Correlations between RT1 and RT2 (panel A), RTs and PL1 (panel B), RTs and PL2 (panel C), and IRI and eSOA (panel D) as a function of SOA in the PRP group of Experiment 1. Asterisks indicate correlations significantly different from zero (one-sample *t*-test; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$). Error bars represent ±1 SE.

2.2.4. Estimated SOA

The eSOA also showed different patterns across SOAs for the two groups (Fig. 3C). In the PRP group, participants overestimated short SOAs but underestimated long SOAs. At zero SOA, the overestimation (213 ms) was similar to the one observed by Marti et al. (about 250 ms). At the longest SOA, however, the underestimation was much smaller (103 ms) than in their study (about 500 ms at an SOA of 1000 ms). Importantly, participants in the control group showed a different pattern. They slightly overestimated the SOA at all SOAs. Nevertheless, the deviation of estimated SOAs from the objective SOAs (63, 40, 30, 78, 18 ms from shortest to longest SOA) was still affected by SOA, $F(4,76) = 4.98$, $p = .013$, $\eta_p^2 = .21$. The difference in eSOAs between the two groups was confirmed by a marginally significant effect of group, $F(1,38) = 3.86$, $p = .057$, $\eta_p^2 = .09$, and a significant interaction between group and SOA, $F(4,152) = 19.88$, $p < .001$, $\eta_p^2 = .34$.

2.2.5. Correlations

There were strong positive correlations between RT1 and RT2 at short SOAs (Fig. 4A). The RT1–RT2 correlation decreased with increasing SOA, $F(4,76) = 5.83$, $p = .005$, $\eta_p^2 = .23$, yet it was still significantly different from zero even at the longest SOA. Correlations between PL1 and RTs were generally weak (Fig. 4B), but the positive correlations between RTs and PL1 at the two shortest SOAs reached significance (at the zero SOA only the correlation between RT1 and PL1 was significant). ANOVAs revealed no significant effect of SOA on RT1–PL1 correlation, $F(4,76) = 1.76$, $p = .146$, $\eta_p^2 = .08$. However, SOA significantly affected the RT2–PL1 correlation, $F(4,76) = 4.40$, $p = .003$, $\eta_p^2 = .19$. Importantly, the results showed a significant RT1–PL2 correlation only for the 40 ms SOA (Fig. 4C). Additionally, the RT1–PL2 correlation was not significantly affected by SOA, $F(4,76) = 1.57$, $p = .210$, $\eta_p^2 = .08$. Instead, PL2 showed stronger relationships with RT2 than with RT1 across SOAs (mean correlation coefficients: 0.16 vs. 0.08). The RT2–PL2 correlations were significant for the three shortest SOAs and decreased with increasing SOA, $F(4,76) = 2.77$, $p = .033$, $\eta_p^2 = .13$. This finding suggests two alternative explanations for the SOA effect on PL2: either the onset of S2 is temporally bound to the Task 2 response or the estimates of the two stimulus onsets are biased by the interval between the two associated responses (inter-response interval, IRI). At short SOAs this would result in a large overestimation of SOAs, as the IRIs are just over 400 ms in all three of the smallest SOAs. In order to evaluate the latter hypothesis for Experiment 1, we analyzed the trial-by-trial correlations between IRI and eSOA (i.e., the difference between the reported positions of S1 and S2 onsets). Consistent with this hypothesis, IRI and eSOA showed significant positive correlations at all SOAs (Fig. 4D).

2.3. Discussion

The results of Experiment 1 demonstrate that in a dual-task situation the specific response requirements associated with the two tasks strongly influence participants' reports of stimulus onsets. When participants provided separate speeded responses to the stimuli (i.e., the PRP group), PL2 was prolonged at short SOAs and linearly decreased with increasing SOA. This pattern was not observed for participants who did not respond to the stimuli (the control group). This finding could be considered evidence for the delayed conscious perception hypothesis which states that response selection for Task 1 causes a delay in the conscious perception of S2. Several other findings, however, raise doubts about such an interpretation. In contrast to the expectation that PL1 should be unaffected by task overlap, we found that PL1 increased with increasing SOA, an effect that was of a similar size (162 ms) as the SOA effect on PL2 (153 ms). It seems rather implausible that this effect might reflect a delay of conscious perception of S1 at long SOAs. The results of the correlational analyses are also largely inconsistent with a delayed conscious perception of S2 due to Task 1 response selection. Even though there was a positive RT1–PL2 correlation at the 40 ms SOA, we could not find evidence for a systematic weakening of this relationship with increasing SOA. Instead, we found a stronger relationship between PL2 and RT2 suggesting that the estimated onset of S2 is associated more strongly with Task 2 processing than with Task 1 processing.

Based on the correlation results we suggest two alternative explanations for the SOA effect on PL2. First, it might reflect temporal binding between the perceived onset of S2 and R2. This hypothesis is consistent with previous findings of efferent binding (e.g., Haggard, Aschersleben, Gehrke, & Prinz, 2002). Usually, efferent binding occurs between intentional actions and action consequences (see Moore & Obhi, 2012, for a review). In such a situation, the perceptual onset of the action consequence is temporally shifted toward the action. However, such binding has also been found for the opposite causal relationship, that is, between an imperative stimulus and the response to the stimulus (Haggard et al., 2002; Exp. 2). According to this *efferent binding* hypothesis, in the present experiment PL2 is longer at short than at long SOAs because the interval between S2 and R2 (i.e., RT2) is longer at short SOAs. Second, the SOA effect on PL2 might also reflect that the estimates of S1 and S2 are biased by the temporal relationship between the two responses (IRI). As at short SOAs the IRIs are much longer than the SOAs, this would result in a large overestimation of SOAs. In turn, S2 onset might be reported at a later position at short SOAs. Such an influence would be reflected in RT2–PL2 correlations because when RT2 increases (and RT1 is held constant), IRI also increases. Consistent with this *response-related estimation bias* hypothesis, IRI and eSOA showed significant positive correlations at all SOAs. We conducted Experiment 2 with the aim of distinguishing among these two new hypotheses and the original delayed conscious perception hypothesis.

3. Experiment 2

In Experiment 2, we directly manipulated the IRI by employing two different response modes: the standard response mode of the PRP paradigm (i.e., separate speeded responses to the two stimuli), and a grouped response mode in which participants were instructed to provide the two responses at the same time (De Jong, 1993; Pashler & Johnston, 1989).

The two response modes should lead to different RT patterns depending on SOA. When grouping the two responses, participants need to withhold R1 until they know the required response for Task 2. Consequently, in this mode they provide R1 later than in the standard response mode, especially at long SOAs. Thus, in the grouped response mode RT1 should increase with increasing SOA whereas in the standard response mode RT1 should be unaffected by SOA. Importantly, response mode should not affect Task 1 perceptual processing and response selection.

According to the delayed conscious perception hypothesis, PLs should be unaffected by response mode, because S2 is perceived once a response has been selected for Task 1, which occurs at the same time regardless of response mode. The efferent binding hypothesis also predicts no influence of response mode on PL2, as R2 (which is the important factor in the efferent binding hypothesis) is expected to be unaffected by response grouping. However, if S1 is also bound to R1, the grouped response mode might lead to an increase of PL1 compared to the standard response mode, since participants need to withhold R1 when they group their responses. In contrast, the response-related estimation bias hypothesis predicts shorter eSOAs and PL2s for the grouped than for the standard response mode because IRIs should be much shorter when participants group their responses.

3.1. Method

3.1.1. Participants

Five males and 35 females, aged between 18 and 28 years ($M = 22.1$ years) participated in a 1 h session. Participants reported normal hearing and normal or corrected-to-normal vision, and received course credit or payment.

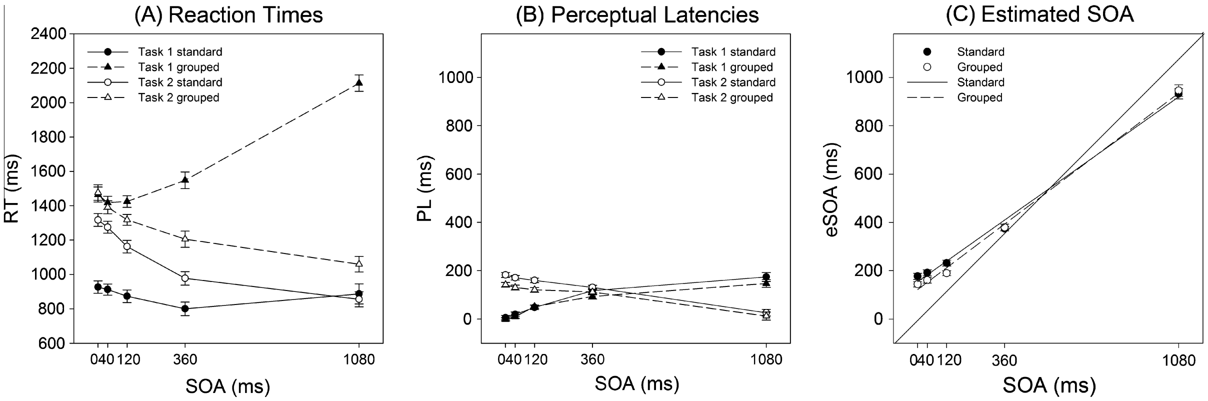

Fig. 5. RTs (panel A), and PLs (panel B) in Task 1 and 2 as a function of SOA and response mode in Experiment 2. Panel C depicts eSOAs (i.e., the interval between the estimates of S1 and S2 onsets) as a function of SOA and response mode; the lines represent the regression lines, and the identity line is shown for the purpose of comparison. Error bars represent ±1 within-subjects SE.

3.1.2. Apparatus and stimuli

The apparatus and stimuli were identical to Experiment 1.

3.1.3. Procedure and design

In one half of the experiment, participants performed the PRP task with the standard instruction (i.e., to respond as quickly and accurately as possible to the two stimuli). In the other half of the experiment, they were asked to group their responses (i.e., to provide the two responses at the same time). The order of the two response mode conditions (standard vs. grouped) was counterbalanced across participants. As in Experiment 1, after each trial, participants provided estimates for the onsets of the two stimuli. Together with the feedback about the correctness of their responses, they received an additional feedback message if they had not followed the response mode instruction. In the grouped condition, the feedback message “Reagiere auf beide Reize gleichzeitig!” (“Respond to both stimuli at the same time!”) was presented if they had produced an IRI larger than 100 ms. In the standard condition, the feedback message “Reagiere so schnell und korrekt wie möglich auf beide Reize!” (“Respond to both stimuli as quickly and as accurately as possible!”) was presented if they had produced an IRI smaller than or equal to 100 ms. In all other respects, the procedure was identical to the one of Experiment 1.

Each session was comprised of two practice blocks (one at the beginning of each half of the experiment) and ten experimental blocks. Each block consisted of four trials at each SOA level, that is, 20 trials in total. Thus, participants performed 100 experimental trials for each response mode condition.

3.2. Results

3.2.1. Data analysis

The data of four participants were excluded and replaced because of either a high proportion of grouped responses in the standard condition (>89%; 3 participants) or an unusually high proportion of trials containing an error in one or both of the two tasks (>37%; 1 participant). We discarded all trials that included an error in Task 1 and/or Task 2 (9.4%). As in Experiment 1, trials with RTs deviating more than three standard deviations from the individual mean in each SOA condition (1.7% of correct trials) and trials with implausible estimates (deviating more than 1000 ms from the objective stimulus onsets, 9.3% of the remaining trials) were discarded from analyses. Separate ANOVAs including the factors SOA (0, 40, 120, 360, or 1080 ms) and response mode (standard vs. grouped) were performed for RT1, RT2, PL1, PL2, and eSOA. Correlation analyses followed the procedure of Experiment 1.

3.2.2. Response grouping

In the standard condition, the proportion of grouped responses (IRI $\leqslant$ 100 ms) was low (3.8%). In the grouped condition, participants grouped their responses in most of the trials (97.5%). Consequently, IRI was much smaller in the grouped than in the standard condition (16 vs. 558 ms). In the standard condition, IRI increased with increasing SOA (390, 402, 409, 537, and 1049 ms), $F(4,156) = 233.04$, $p < .001$, $\eta_p^2 = .86$, whereas in the grouped condition IRI was rather constant across SOAs (12, 14, 14, 16, 26 ms), $F(4,156) = 1.42$, $p = .248$, $\eta_p^2 = .04$. These results confirm that the manipulation of response mode was successful.

3.2.3. Reaction times

Fig. 5A shows RT1 and RT2 as a function of SOA and response mode. An ANOVA for RT1 revealed a main effect of SOA, $F(4,156) = 47.17$, $p < .001$, $\eta_p^2 = .55$, a main effect of response mode, $F(1,39) = 106.03$, $p < .001$, $\eta_p^2 = .73$, and an interaction

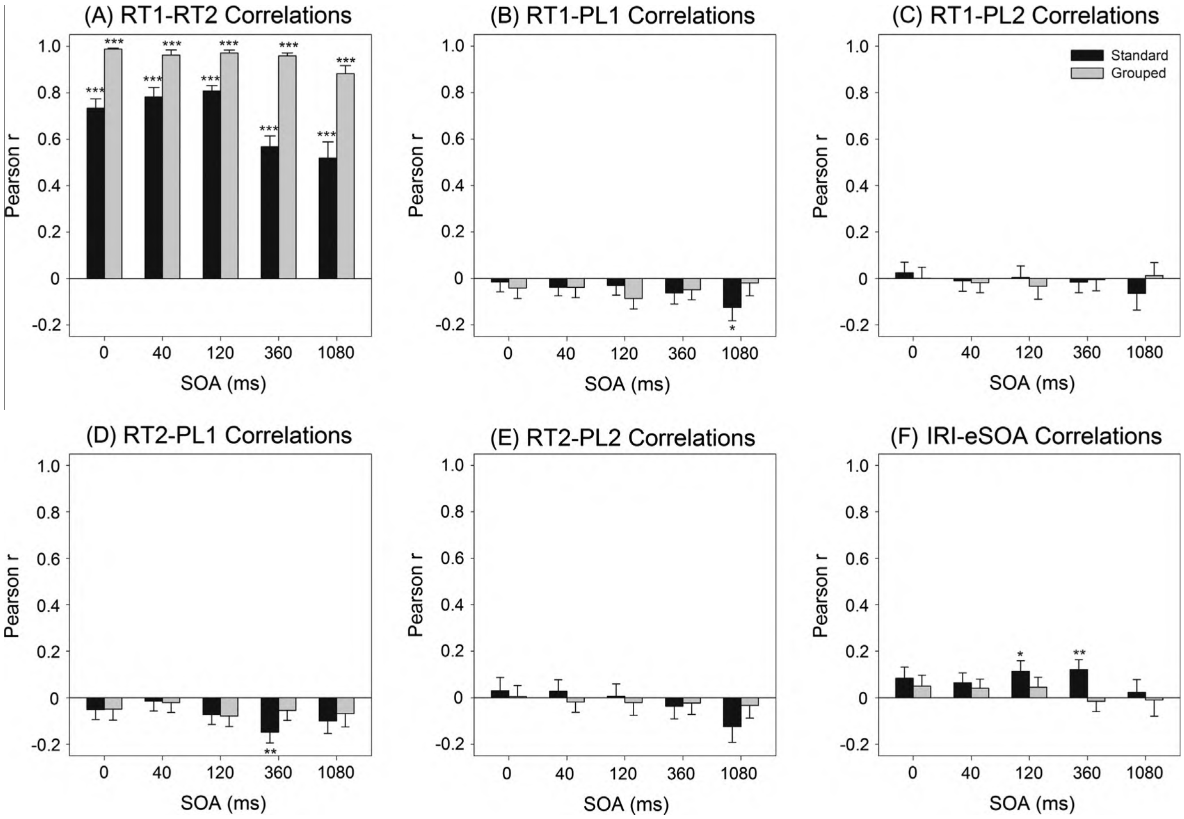

Fig. 6. Correlations between RT1 and RT2 (panel A), RT1 and PL1 (panel B), RT1 and PL2 (panel C), RT2 and PL1 (panel D), RT2 and PL2 (panel E), and IRI and eSOA (panel F) as a function of SOA and response mode (standard vs. grouped) in Experiment 2. Asterisks indicate correlations significantly different from zero (one-sample *t*-test; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$). Error bars represent ±1 SE.

of SOA and response mode, $F(4,156) = 85.46$, $p < .001$, $\eta_p^2 = .69$. As one would expect, RT1 in the grouped condition increased with increasing SOA, whereas RT1 in the standard condition showed little variation across SOAs. RT2 exhibited the standard PRP effect, $F(4,156) = 89.08$, $p < .001$, $\eta_p^2 = .70$. In contrast to previous studies (De Jong, 1993; Pashler & Johnston, 1989), RT2 was also affected by response mode, $F(1,39) = 6.68$, $p = .001$, $\eta_p^2 = .15$. RT2 was 173 ms longer in the grouped condition than in the standard condition. This finding suggests that grouping responses also resulted in a cost in giving the second response. However, the size of the PRP effect was not affected by response mode (461 ms in the standard vs. 418 ms in the grouped response mode), as there was no interaction of SOA and response mode on RT2, $F(4,156) = 1.91$, $p = .112$, $\eta_p^2 = .05$.

3.2.4. *Perceptual latencies*

Fig. 5B depicts PL1 and PL2 as a function of SOA. As in Experiment 1, SOA affected the two PLs in opposite directions. PL1 increased from the zero SOA (2 ms) to the longest SOA (161 ms), $F(4,156) = 48.14$, $p < .001$, $\eta_p^2 = .55$, whereas PL2 decreased from the zero SOA (162 ms) to the longest SOA (19 ms), $F(4,156) = 35.72$, $p < .001$, $\eta_p^2 = .48$. Importantly, response mode affected PL2, $F(1,39) = 10.19$, $p = .003$, $\eta_p^2 = .21$, but did not affect PL1, $F(1,39) = 2.10$, $p = .156$, $\eta_p^2 = .05$. Consistent with the response-related estimation bias hypothesis, PL2 was 31 ms smaller in the grouped than in the standard condition. There was no interaction of SOA and response mode for PL1 or PL2, $ps > .268$.

3.2.5. *Estimated SOA*

As in the PRP group of Experiment 1, participants overestimated short SOAs and underestimated long SOAs (Fig. 5C). An ANOVA revealed a main effect of SOA, $F(4,156) = 593.31$, $p < .001$, $\eta_p^2 = .94$, but no main effect of response mode, $F(1,39) = 2.65$, $p = .112$, $\eta_p^2 = .06$. Importantly, the interaction of SOA and response mode was significant, $F(4,156) = 3.46$, $p = .032$, $\eta_p^2 = .08$. As can be seen in Fig. 5C, participants estimated the SOA to be smaller in the grouped than in the standard condition especially at short SOAs. This finding again suggests that the IRI influences how participants estimate the SOA.

3.2.6. *Correlations*

In the standard condition, the correlations between RT1 and RT2 across SOAs (Fig. 6A) were very similar to Experiment 1. As one would expect, these correlations were even stronger in the grouped than in the standard condition at all SOAs.

Irrespective of response mode, correlations between RTs and PLs were mostly negative and non-significant (Fig. 6B–E). The correlations between IRI and eSOA were weaker than in Experiment 1 (Fig. 6F). Nevertheless, in the standard condition, the positive correlations at the 120 and the 360 ms SOA were significant.

3.3. Discussion

The PL results of Experiment 2 were comparable to those of the PRP group in Experiment 1. That is, Experiment 2 replicated both the SOA effect on PL2 and the rather surprising finding that PL1 increased with SOA. Within the delayed conscious perception hypothesis, there is no plausible reason for the conscious perception of S1 to be delayed at long SOAs. Therefore, we remain reluctant to interpret longer PL2s at short SOAs as reflecting a delayed conscious perception of S2. Importantly, the results of Experiment 2 showed that response mode affected participants' estimates of stimulus onsets, a finding that is also in conflict with the delayed conscious perception hypothesis. In comparison to the standard response mode, response grouping greatly reduced IRIs, delayed both responses, and shortened PL2 but did not affect PL1. Importantly, while short SOAs were overestimated in both response modes, response grouping also reduced this overestimation. These findings largely support the response-related estimation bias hypothesis. Even though correlational analyses were less informative in this experiment than the previous, the significant correlations between IRI and eSOA also support the response-related estimation bias hypothesis. Further, PL results argue against the efferent binding hypothesis, which states that the perception of S1 and S2 is drawn toward the relevant response. Even though participants provided the two responses later in the grouped than in the standard response mode, PL results indicate that S1 and S2 were not perceived later. Rather, PL2 was shorter in the grouped than in the standard response mode.

4. General discussion

The main aim of the present study was to test whether response selection for one task delays the conscious perception of another stimulus (delayed conscious perception hypothesis). For this purpose, we combined the PRP paradigm with the clock paradigm and assessed perceptual latencies of S1 and S2 (i.e., the deviation of perceived stimulus onsets from their objective onsets). The delayed conscious perception hypothesis predicts that at short SOAs, PL2 is prolonged and related to RT1. The results of Experiment 1 and 2 confirmed the first prediction but not the second. Instead, in Experiment 1 we found that PL2 was more strongly related to RT2 than to RT1 and that the estimated interval between the stimulus onsets (i.e., eSOA) was related to the interval between the responses (i.e., the IRI). Further, the finding that PL1 increased with SOA is also not consistent with the delayed conscious perception hypothesis. Based on the correlation results of Experiment 1, in Experiment 2 we tested two alternative accounts of the misperception of S2 onset and SOA. First, the perceived onsets of the stimuli might be temporally bound to their corresponding responses (efferent binding). Second, participants might be biased by the IRI when estimating the stimulus onsets (response-related estimation bias). In Experiment 2, we found that response grouping reduced both PL2 and the misperception of SOA. Thus, the results largely support the response-related estimation bias hypothesis.

A rather surprising but consistent finding of this study was that PL1 increased with increasing SOA. That is, estimates of S1 onset deviated maximally from the objective S1 onset when the two tasks were temporally separated. While none of the three hypotheses predicted this effect, it can be easily reconciled with the response-related estimation bias hypothesis. The PL1 results suggest that rather than having stable representations of each stimulus onset, participants have an internal representation of the SOA and of only one stimulus onset, which acts as an anchor for the other estimate. That is, in order to provide the estimate of the other stimulus onset, participants would add or subtract their representation of SOA to/from this anchor position. If participants most often use S1 as an anchor at short SOAs, and S2 as an anchor at long SOAs, this would lead to the observed opposite effects of SOA on PL1 and PL2, namely an increase of PL1 and a decrease of PL2 with increasing SOA. This raises the question, why would the 'anchor' stimulus change across SOAs? It could be that with increasing SOA it becomes more difficult to remember the onset of S1 for two reasons – total trial length increases, and more time elapses between the onsets of the two stimuli.

One finding that is not consistent with a strict version of the response-related estimation bias hypothesis is that response grouping in Experiment 2 did not eliminate the SOA effect on PL2. That is, even when IRI was very small and rather constant across SOAs, PL2 was still prolonged at short SOAs. This implies that a response-related estimation bias cannot wholly account for the misperception of SOAs. It could be that participants also use the interval between their decisions about each task as a proxy for SOA, which is presumed to be unaffected in the grouped response mode. Another possibility is that the representation of SOA in a given trial is not only biased by the IRI in that trial, but also by an average representation of all SOAs experienced across the experiment. Such a bias would lead to an overestimation of short intervals and an underestimation of long intervals, a pattern often denoted as Vierordt's law (e.g., Wearden & Lejeune, 2008). Notably, this pattern was not observed in the control group of Experiment 1. This suggests that such a bias did not contribute to the estimates of stimulus onsets when there were no response requirements and therefore attentional demands were reduced. Another inconsistency with the response-related estimation bias hypothesis is the lack of positive RT2–PL2 correlations in the standard response mode condition of Experiment 2. However, the correlations in Experiment 2 were generally weaker and less informative than the correlations in Experiment 1.

Unexpectedly, the control group of Experiment 1 also showed SOA effects on both PLs. That is, although control participants did not respond to the two stimuli, their reports of stimulus onsets were still affected by the temporal proximity of the stimuli. Most notably, reports of S2 onset as well as eSOA showed the largest deviations from the objective values at the 360 ms SOA (see Fig. 3B and C). These effects cannot be explained by participants basing their estimates on an averaged representation of SOAs. Instead, the notion of attentional episodes, referred to in the episodic Simultaneous Type/Serial Token (eSTST) model (e.g., Wyble, Potter, Bowman, & Nieuwenstein, 2011), may be able to account for these effects. According to this notion, when two stimuli appear simultaneously or in close succession (<200 ms) they are encoded within one attentional episode. When they are separated by a short temporal gap, the encoding of the second stimulus is delayed in order to promote the episodic distinctiveness of the two stimuli. Such a delayed encoding could explain the large deviations at the 360 ms SOA. However, it remains unclear why the estimates of S2 and eSOAs were still larger at the shortest than at the longest SOA. The eSTST model would assume that two simultaneously presented stimuli are encoded within the same attentional episode and therefore should be consciously perceived at roughly the same time. It should be noted that the eSTST model was developed to account for the visual attentional blink. While such a model might also apply to other modalities, some authors have argued that cross-modal attentional blink effects reflect a task-switch deficit that arises when a switch between tasks or perceptual sets is required (Potter, Chun, Banks, & Muckenhoupt, 1998). As we employed an auditory S1 and a visual S2, such a task-switch deficit might have also affected PLs in the present study. Additionally, there is evidence that saccadic eye movements can distort the perception of time (Morrone, Ross, & Burr, 2005). Since participants had to follow the clock hand with their eyes, such eye movements might have contributed to the observed misperception of stimulus onsets. However, recent findings by Wyble, Potter, and Mattar (2012) suggest that such influences are minimal. These authors conducted an attentional blink study in which a stream of stimuli was presented either stationary or in a circular motion. They found no attentional blink effect in the motion condition when the participants fixated centrally. However, comparable attentional blink effects occurred in the stationary condition and in the motion condition when participants followed the moving stimuli with their eyes.

Another commonly used method to compare perceptual latencies in different conditions is the temporal order judgment in which participants are asked to indicate which of two stimuli appeared first. Such an approach has been applied to the PRP task in a study by Hendrich, Strobach, Buss, Müller and Schubert (2012; see also De Jong, 1995). In this study, participants were asked in one condition to simply judge the temporal order of two stimuli (a tone and a digit) that were presented with different SOAs and in varying order. This purely perceptual condition was compared to the PRP condition in which participants provided speeded responses to the stimuli. Since the participants were instructed to respond in the order of stimulus presentation, the authors posited that response order in the PRP task could be interpreted in the same way as the temporal order judgment in the perceptual task. That is, response order should reflect the order in which participants perceived the two stimuli. Similar to our results of Experiment 1, Hendrich et al. found that task processing requirements affected temporal order judgments. When performing the PRP task, participants appeared to have a preference to respond to the tone first. While this finding could be interpreted as an effect of task requirements on the perceptual latencies of the two stimuli, the authors suggested that participants in the PRP task may have responded first to the auditory task because the visual task was more challenging (in the visual task the perceptual stage was manipulated). Thus, it is unclear how response order is related to the conscious perception of stimuli, which makes it hard to draw any conclusions from this study regarding the conscious perception of the two stimuli.

In the Introduction, we noted that in previous introspective PRP studies the use of visual analogue scales might have introduced a bias to the participants' reports. Since we found similar misperceptions of SOA here, the present study argues against the possibility that previous findings of an overestimation of short SOAs were due to methodological issues associated with the use of visual analogue scales. The present findings rather suggest that, irrespective of the introspective method, introspection in the PRP paradigm is prone to several biases, such as a response-related estimation bias and reliance on an average representation of SOAs. In that context, we suggest that such biases affect not only estimates of stimulus onsets in the clock paradigm but also estimates of RTs and SOAs collected via visual analogue scales. More generally, our findings suggest that participants often refer to potentially misleading sources of information when they are asked to provide introspective reports about the timing of their own performance and the objective events in a PRP trial. In fact, there is evidence that introspective RTs can also be biased by the feeling of difficulty experienced by the participant in a given trial (Bryce & Bratzke, 2014). Presumably, in the PRP task, in which the dual-task itself places heavy demands on attentional resources, timing abilities are reduced (see also Ruthruff & Pashler, 2010), and the information from these other sources is especially salient and accessible.

In conclusion, the present results suggest that in a dual-task situation S2 onset is misreported not because attentional resources needed for conscious perception are tied up with Task 1 response selection but rather because estimates are biased by several other sources. Nevertheless, our results do not rule out the delayed conscious perception hypothesis. It could be that participants refer to especially salient but potentially misleading temporal cues (e.g., the IRI) to infer specific time points within the temporal course of a PRP trial (e.g., perceived stimulus onsets) because their conscious perception of events is disrupted while the response for Task 1 is being selected. Other approaches may be required to assess the precise points in time when participants become consciously aware of the stimuli in a PRP task. The present study, however, demonstrates that results obtained with introspective methods are especially difficult to interpret and such interpretations may not withstand closer scrutiny. This highlights a considerable challenge facing research investigating the relationship between attention and consciousness.

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