Investigation of reward-related processing improvements in dual-task situations

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Table of Contents

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2. Abstract

Evidence from single task studies indicates that the prospect of reward improves a variety of cognitive processes, while, for dual-tasking (DT) situations, reward-related processing improvements are only poorly specified. As a consequence, I investigated four core issues that remained unanswered in previous investigations. The first issue was which cognitive processes are affected by the prospect of reward in the processing chain of two tasks. The second issue, related to whether reward-related processing improvements are transmitted between tasks. The third issue, related to whether participants can flexibly switch their reward processing strategy, between trials, to improve their DT performance. Finally, the fourth issue, related to the current discussion on whether reward-related processing improvements reflect, in essence, improved preparation. To tackle issue one and two, I combined the psychological refractory period (PRP) paradigm with a task-selective reward prospect to either task 1 (Study 1) or task 2 (Study 2). For such PRP DT conditions, it is assumed that a bottleneck emerges between task 1 and task 2, for conditions of large in contrast to small temporal overlap of the processing chains. Across both studies, the chronometric analysis, applied to infer the locus of the reward effect, indicated that mainly pre-motoric processes of the first task (task 1) were improved and these reward-related processing improvements were transmitted via the bottleneck mechanism onto the processing chain of the second task (task 2). Thus providing evidence on the locus of the reward effect and for reward-related transmission effects between tasks. To investigate issue three, I applied a trial-wise reward prospect, signaled by a cue, prior to task 1 onset. Consequently, participants had to switch their reward processing strategy, between trials, to obtain a reward. The results indicated that task 1 and task 2 performance were improved, again, demonstrating a reward-related processing transmission between tasks. To investigate issue four, I additionally, varied the cue-target-interval (CTI), resulting in a CTI of 200 ms or 700 ms, to investigate how the size of the reward effect is affected by the length of the preparatory interval. The results demonstrated that task 1 and task 2 performance was improved for the longer CTI compared to the shorter CTI. However, at the same time, the reward effect was increased in the long compared to the short CTI condition on task 1 and task 2 performance. Consequently, these results, provided evidence consistent with the assumption, that the prospect of reward led to further processing improvements, beyond a mere preparation effect, which suggest that preparation is not sufficient to explain reward-related processing improvements. The implications of the results as well as an outlook for future research will be discussed.

3. List of original research articles

The dissertation is based on three original research articles:

Article 1

Langsdorf, L. E., Kübler, S., & Schubert, T. (2022). Investigation of reward effects in overlapping dual-task situations. *Acta Psychologica*, *222*, 103465. https://doi.org/10.1016/j.actpsy.2021.103465

Article 2

Langsdorf, L. E., Darnsteadt, D., & Schubert, T. (2025). On the localization of reward effects in overlapping dual tasks. *Psychological Research, 89*(1), 20. https://doi.org/10.1007/s00426-024-02054-4

Article 3

Langsdorf, L. E. & Schubert, T. (2025). On the temporal dynamics of reward utilization in dual tasks. *Attention, Perception & Psychophysics, 87*(4), 1249-1269. https://doi.org/10.3758/s13414-025-03058-x

4. Introduction

People usually show impaired task performance when executing multiple tasks at the same time. It is challenging to run and cross a ball to a teammate compared to just execute one of these tasks. One possibility, to improve the running performance could be the prospect of reward, potentially leading to increased running velocity. However, how would that affect our ability to cross the ball? To date, scientific research has largely overlooked how the prospect of reward affects dual-task (DT) performance, leading to a lack of understanding which cognitive processes might be affected by the prospect of reward.

In the last decades, the scientific inquiry focused on the investigation of the cognitive processing architecture during DT situations, producing a rich set of paradigms, such as the overlapping DT approach (Fischer & Plessow, 2015; Pashler, 1994). A usual observation in this paradigm is that DT performance deteriorates compared to when the same tasks are performed in isolation, the resulting DT costs, can be explained with processing limitations of the central stages (Pashler, 1994; Schubert, 1999).

A substantial amount of previous research focused on the modulation of processing limitations in DT situations, applying a rich set of interventions, while largely neglecting how motivation in the form of a reward prospect affects DT processing. While, recently this research focus shifted, leading to the investigation of how the prospect of reward affects DT processing, the evidence is mixed. In particular, some studies reported that the prospect of reward can improve DT processing (Charron & Koechlin, 2010; Fischer et al., 2018; Han & Marois, 2013), while other studies reported mixed evidence (Rieger et al., 2021; Yildiz et al., 2013). Related to that, several relevant issues remained unanswered in these investigations, such as, which cognitive processes are improved by the prospect of reward. The second open issue is, whether the prospect of reward to one task leads to processing improvement to the other task as well. A third open issue is, whether participants can flexibly switch their reward processing strategy in DT situations. Finally, a fourth open issue is, whether reward-related processing improvements, reflect in essence, improved preparation, as currently discussed (Kleinsorge & Rinkenauer, 2012; Rieger et al., 2021). The present dissertation aimed to investigate the outlined open issues, to specify how the prospect of reward affects DT processing.

4.1 Overview of the present work

In the subsequent Chapter 5, I will outline the assumption of the central bottleneck model and the paradigm of the psychological refractory period (PRP), which where applied in the present dissertation. The paradigm of the monetary incentive delay task (MID) which was applied to induce reward-related processing improvements, will be introduced in Chapter 6. To derive the first and second issue, that I investigated, I will present previous evidence of how the prospect of reward affects cognitive processing in sensory-motor reaction time (RT) tasks in Chapter 7. In Chapter 8, I will introduce previous evidence on reward applications in DT situations, deriving the third issue. Subsequently, in Chapter 9, I will outline the fourth issue, by illustrating the current discussion on a potential mechanism driving reward-related processing improvements. The research questions, for Study 1-3 will be outlined in Chapter 10. In Chapter 11-13, I will describe and discuss the Studies 1-3. In Chapter 14, I will discuss the results and implications, as well as further directions of research.

5. Central processing limitations in dual-tasks

As I highlighted earlier, the processing and execution of two tasks at the same time, poses challenges for the cognitive system. These processing limitations can be investigated with the PRP paradigm, in which participants are asked to execute two discrete choice RT tasks (Pashler, 1994). As a result, it is reasonable to assume that the processing chain of each task can be decomposed into discrete processing stages. Consequently, this enables the application of chronometric methods such as the effect propagation and locus-of-slack logics which are applied to localize the effect of an experimental manipulation in the processing chain of a PRP DT situation (Posner, 1986; Schweickert, 1978, 1980).

The PRP paradigm, comprises of two choice RT tasks, separated by a variable temporal interval the stimulus-onset asynchrony (SOA) (Pashler, 1994; Welford, 1959). In that task situation, participants are instructed to respond to both tasks as fast as possible, while emphasizing not to withhold the first response until the second stimulus is presented (Ulrich & Miller, 2008). This usually results in an increasing RT of task 2 (RT2) with decreasing SOA, while the resulting cost at short SOA, in contrast to long SOA is described as the PRP effect (Pashler & Johnston, 1989; Schubert, 1999). Concerning the RT of task 1 (RT1), a strong theoretical prediction assumes no effect of the SOA manipulation on RT1, however, in practice a slight SOA effect on RT1 can be observed (Strobach et al., 2015).

5.1 Explanation of the psychological refractory period effect

The central bottleneck model accounts for the PRP effect by proposing a processing architecture in which each of the processing stages can only start being processed after the previous processing stage has been fully processed (Pashler, 1994; Pashler & Johnston, 1989; Schubert, 1999; Schubert et al., 2008; Welford, 1959). During the perceptual stage, a perceptual analysis of the stimulus is conducted, while during the response selection stage, the perceptual information is bound to the required response. Finally, during the motor stage, the initiation and execution of the motor response is computed. The model further contains assumptions about serial and parallel processing of the processing stages. In particular, the peripheral stages, i.e. the perceptual and motor stages are processed in parallel whereas, central stages, i.e. the response selection of the first task (task 1) and the second task (task 2), can only be processed serially. Hence, the bottleneck is located at the central stages resulting in serial processing of the response selection stages of task 1 and task 2.

The RT predictions of the model follow the described theoretical assumptions predicting an increased RT2 for short in contrast to long SOAs, due to the temporal overlap of the processing chains resulting in the serial processing of the response selection stages. In particular, only after the response selection of task 1 has been processed, the process of the response selection of task 2 can start, resulting in the so called slack-time - the waiting time until the response selection of task 2 can be processed. In contrast to short SOAs, for long SOAs RT2 is predicted to decrease, as the response selection of task 1 has been processed before the requirement to process the response selection of task 2. As a result the model predicts that RT2 varies as a function of SOA. Taken together, the central bottleneck model proposes a structural processing limitation at the central stages in the processing chain of both tasks resulting in the serial processing of the response selection stages of task 1 and task 2.

Since the introduction of the central bottleneck model, several competing models have been proposed some of them challenging the core assumption of a serial processing of the central stages (Logan & Gordon, 2001; Meyer & Kieras, 1997). While some models proposed central capacity sharing (Navon & Miller, 2002; Tombu & Jolicœur, 2003) other models, such as the *response initiation bottleneck model* propose that the bottleneck emerges during the processing of the motor stages of both tasks (Bratzke et al., 2008; Karlin & Kestenbaum, 1968). Taken together, there are DT circumstances during which a parallel or semi-parallel processing of the central stages is possible, however, all of the mentioned models advocate the idea of impaired DT in contrast to single task performance.

For the PRP DT situations in Study 1-3, I assumed that a central bottleneck interrupts the processing chain of task 1 and task 2. Consequently, I utilized this assumption to investigate how the prospect of reward affects DT processing in PRP DT situations.

6. The prospect of reward and the monetary incentive delay task

Research in the last two decades could verify that the prospect of reward improves a wide range of cognitive processes, such as visual attention, cognitive control, cognitive flexibility, motor preparation and many more (Bräutigam et al., 2024; Bundt et al., 2016; Chiew & Braver, 2016; Engelmann & Pessoa, 2007; Kiss et al., 2009; Krebs et al., 2010; Krebs & Woldorff, 2017; Shen & Chun, 2011). In most of these studies the MID task was applied to investigate reward-cognition interactions in sensory-motor RT tasks. In the subsequent paragraph, I will describe the MID task, which was applied in the present dissertation.

6.1 The paradigm of the monetary incentive delay task

For the MID task a cue signals the participants whether or not a reward (e.g. primary or secondary) will be obtainable, accordingly, if a prospect of reward is signaled, task performance will be rewarded according to the reward scheme. Participants usually receive feedback, which can be applied after each trial or block providing information on accuracy, mean RTs and the earned reward to enable performance monitoring (Knutson & Cooper, 2005; Schultz et al., 1997; Wise, 2004). An overly stable finding is that the prospect of reward improves task performance, as reflected by reduced RTs in the reward compared to the no reward conditions. This performance improvement is assumed to be associated with improved proactive control processes triggered by the prospect of reward and facilitating target processing (Braver, 2015; Chiew & Braver, 2016; Jimura et al., 2010; Kouneiher et al., 2009; Krebs & Woldorff, 2017; Locke & Braver, 2008). These reward-related processing improvements are mirrored by results of imaging studies applying the MID task, which demonstrated that the prospect of reward leads to increased activity in regions of the dopaminergic system, such as the ventral striatum (VS) a central region of the human reward-processing system (Haber & Knutson, 2010). In sum, the application of the MID task results in stable reward-related processing improvements for a wide range of cognitive processes enabling the investigation of reward-cognition interactions in sensory-motor RT tasks.

To further investigate reward processing strategies, the prospect of reward can either be applied for an entire block, i.e. block-wise, or on a trial-to-trial basis, i.e. trial-wise. For a block-wise MID task situation, participants can prepare in advance their reward-induced processing strategy for the rewarded block, leading to a sustained mode of reward processing, as reflected by reduced RTs in the reward compared to the no reward condition (Locke & Braver, 2008). In contrast, in a trial-wise MID task situation, participants are required to flexibly utilize the information to switch their reward processing strategy between trials. For such a case, it is proposed that transient control processes are necessary to utilize the reward information on a trial-to-trial basis for adjusting task performance

(Chiew & Braver, 2013, 2016). Taken together, the application of block- or trial-wise reward applications, enables the investigation of reward processing strategies, revealing the temporal resolution of reward-related processing improvements (Krebs & Woldorff, 2017).

6.1.1 The physiological basis of reward-related performance improvements in sensory-motor reaction time tasks

The underlying physiological mechanism of reward-related performance improvements in sensory-motor RT tasks are not entirely clear yet. As a result, it remains an open issue how the brain areas associated with the encoding of the reward information translate these signals into performance improvements at the behavioral level. One central brain area is the VS, which is associated with reward-related performance improvements at the behavioral level, as increased activity levels measured within the VS were closely associated with reward-related performance improvements in sensory-motor RT tasks (Krebs et al., 2011; Liljeholm & O'Doherty, 2012; Pleger et al., 2008). These findings led to the assumption that the VS serves as a motivational node for integrating reward-related signals at the physiological level. As the VS is innervated by dopaminergic neurons which respond to the prospect of reward with the release of dopamine, it is discussed whether this mechanism contributes to the translation of reward signals into performance improvements at the behavioral level (Gan et al., 2010).

7. Reward-related processing improvements in sensory-motor reaction time tasks

Previous studies investigating how the prospect of reward affects DT processing provided inconclusive results, some reporting improved DT performance in the reward compared to the no reward condition (Charron & Koechlin, 2010; Fischer et al., 2018), while others reported mixed results (Rieger et al., 2021; Yildiz et al., 2013). In addition, previous results of single task studies provided divergent loci of the reward effect in the processing chain of sensory-motor RT tasks, i.e. on the perceptual stage, the response selection stage or on the motor stage. As a result, it is an open issue, which processing stage(s) will be affected by the prospect of reward in a DT situation. Below, I will discuss recent evidence indicating the divergent loci of the reward effect in sensory-motor RT tasks.

A further relevant issue is whether reward-related processing improvements of one task, will lead to improved task performance in the other task, as well. Such reward-related transmission effects could indicate a central feature of reward processing not only in task situations with multiple tasks but potentially also in an applied context. For that matter, I will additionally present recent evidence, investigating reward processing in PRP DT situations.

7.1 Reward effects on the perceptual, response selection and motor stages in sensory-motor reaction time tasks

Previously, Engelmann & Pessoa (2007) investigated, the effect of reward prospect on selective visual attention. To that end, participants performed an exogenous spatial cueing task, in which they reported the location of a peripherally cued target stimulus, a faint red dot, which was either superimposed on a face or a house stimulus. Prior to each trial, a cue indicated the reward magnitude that was obtainable in the upcoming trial. The authors reported a linear increase in detection sensitivity measured by d prime as a function of reward magnitude. These results can be interpreted with the assumption that the reward prospect sharpened the perceptual focus improving perceptual processing.

There is further evidence for the assumption of an early loucs of the reward effect in the processing chain of a sensory-motor RT task. In a study by Kiss et al. (2009), the effect of reward prospect on visual selection was investigated. In particular, electrophysiology was applied, with high temporal resolution while participants were asked to search for a color singleton (i.e. target with unique color) among distractors to discriminate whether the notch of the target was either pointing up or down. The authors reported that for high reward compared to low reward targets the physiological correlate of visual processing emerged earlier and was larger while being paralleled by faster discrimination performance. The authors concluded that the prospect of reward rapidly modulated the visual processing of the target. Taken together the results indicate that the prospect of reward can improve early perceptual processes in the processing chain of a sensory-motor RT task.

In contrast, there are also studies which indicate that the prospect of reward might affect the response selection process. In a recent study, Chiew & Braver (2016) explored the combined effect of reward prospect and prior task information, on task performance in an Erikson flanker task. In Experiment 1, during each trial a cue indicated whether a reward was obtainable or not, and whether the following task situation would be congruent or incongruent. The authors provided evidence that the reward prospect *and* prior task information overadditively improved task performance. This effect pattern is in line with other studies indicating a potential link between reward prospect and effects on the response selection process (Etzel et al., 2016).

In addition, several studies provided evidence for the assumption that motor-related processes can be affected by the prospect of reward. In an investigation by Bundt et al. (2016), the participants were asked to perform a horizontal Simon task. Prior to each trial a cue indicated whether reward was obtainable or not. The authors provided evidence for the assumption that the prospect of reward led to enhanced motor preparation, as indicated by reduced motor evoked potentials after the cue signaled the prospect of reward in cortical regions stimulated by transcranial magnetic impulses compared to when no reward was obtainable. This finding is in line with other findings which indicate a close link between the prospect of reward and improved motor preparation (Chiu et al., 2014; Hollerman et al., 1998; Schultz, 2000).

In sum, the discussed evidence from single task studies on the locus of the reward effect provided inconclusive results, with divergent loci of the reward effect in the processing chain of sensory-motor RT tasks. As a result, a suitable tool, to resolve this issue, is the application of chronometric methods, to pinpoint the locus of the reward effect in the processing chain of PRP DT situations.

7.1.1 No reward-related transmission effects between tasks in dual-task situations

For DT situations, it is conceivable, that reward-related processing improvements of one task, could also improve the processing time of the other task, via the bottleneck mechanism. However, previous evidence on reward-related transmission effects between tasks, is inconclusive (Fischer et al., 2018; Rieger et al., 2021; Yildiz et al., 2013). Consequently, this raises the issue of whether reward-related processing improvements can be transmitted, via the bottleneck mechanism, between tasks, or whether the bottleneck prevents the transmission of reward effects.

In particular, Rieger et al. (2021), investigated reward effects on task performance across DT paradigms. For the case of the PRP DT paradigm, participants were asked to discriminate letters and the colored frame around the letters. The reward prospect was applied block-wise, with either a high reward to task 1 and low reward to task 2 or vice versa. The authors reported that a high reward prospect to task 1 (compared to a low reward prospect) *only* improved task 1 processing but *not* task 2 processing; similarly a high reward prospect to task 2 (compared to a low reward prospect) did also *not* improve the task 2 processing time. The authors inferred that the lacking reward effect on task 2 performance could be related to the need to coordinate two motor responses, which might have impeded an improved task 2 preparation.

An alternative reason for the absence of reward-related task 2 improvements could be the selection of trials for the analysis of reward effects on task performance by Rieger et al. (2021). In particular, the authors, selected trials in which participants had either only responded to task 1 (no-go task 2 trial) or only to task 2 (no-go task 1 trial). Thus, for the first case, participants had responded to task 1 but not to task 2, as a result, it is not possible to detect a reward-related processing improvement that is transmitted from task 1 onto the task 2 processing time. For the second case, participants had not responded to task 1 but only to task 2. Here it is conceivable, that the reward effect emerges during the task 1 processing time which is subsequently transmitted via the bottleneck mechanism onto the task 2 processing chain. Thus, selecting trials in which participants had *not* responded to task 1, could prevent reward effects on the task 2 processing time. Consequently, to investigate the issue of reward-related transmission effects between tasks, proper DT conditions are required comprising two responses.

8. Reward processing strategies in dual-task situations

A further open issue, relates to the investigation of reward processing strategies in DT situations, which has only been studied fragmentary. In particular, previous studies, investigating reward processing in DT situations, applied variants of a block-wise reward prospect (Fischer et al., 2018; Rieger et al., 2021; Yildiz et al., 2013). As a result, it is an open issue, whether the reported reward-related processing improvements depend on a block-wise reward application, in which participants can implement their constant strategy of reward-induced preparation, or whether participants can flexibly switch their reward processing strategy between trials.

In detail, Fischer et al. (2018), investigated how the prospect of reward affects between-task interference in DT situations. For their Experiment 2, participants were asked to discriminate digits as task 1 and task 2. After participants had completed a baseline condition, the reward phase started for which task 1 and task 2 performance was rewarded. In the reward phase, a cue signaled randomly alternating rewarded or nonrewarded mini-blocks of 24 trials. For Experiment 3, the reward application was applied between-subjects, resulting in a rewarded and a nonrewarded group condition. As a result, participants faced a constant prospect of reward for which they could apply a constant reward processing strategy, across experiments. Taken together, previous DT studies, applied variants of a block-wise reward prospect (Rieger et al., 2021; Yildiz et al., 2013), as a result, it remains an open issue, whether participants can flexibly switch their reward processing strategies, between trials, and if so, how this would affect DT processing.

9. Reward- and preparation-related processing improvements

Proceeding from the development of a trial-wise reward application for DT situations, I furthermore aimed to investigate the issue of reward- and preparation-related processing improvements. In particular, there is an ongoing discussion, on the mechanism driving reward-related processing improvements, for which some authors assume, that reward-related processing improvements reflect in essence preparation-related processing improvements (Capa et al., 2013; Kleinsorge & Rinkenauer, 2012; Rieger et al., 2021; Zedelius et al., 2012). Consequently, it is proposed that the prospect of reward leads to improved task preparation, as reflected by improved RTs in the reward compared to the no reward conditions, as well as, to improved cortical potentials associated with task-related preparatory processes (Schevernels et al., 2014). In contrast, it is an open issue, whether the prospect of reward could lead to *further* processing improvements on top of the preparation-related processing improvements, which could indicate that the prospect of reward triggers additional cognitive processes. In sum, while several studies provided evidence consistent with the assumption that the prospect of reward improves task performance, the interplay of reward prospect and preparation requires further investigation.

Consequently, to investigate the relation of reward- and preparation-related processing improvements in DT situations, I adopted a research approach, which was developed to investigate effects of temporal preparation on task performance. Therefore, in the next paragraph I will described the methodology as well as previous findings, indicating how temporal preparation modulates task performance. Thereafter, I will describe previous evidence on the interplay of temporal preparation and the prospect of reward.

9.1 Temporal preparation and its effect on task performance in sensory-motor reaction time tasks

Usually studies that investigate temporal preparation insert preparatory intervals, with varying length after cue offset but before target onset. As a result, this application of varying preparatory intervals can modulate task performance in sensory-motor RT tasks, demonstrating the temporal preparation effect (Fischer et al., 2007; Leuthold et al., 2004; Niemi & Näätänen, 1981; Teichner, 1954).

In a previous investigation of Fischer et al. (2007) different conditions of temporal preparation for target processing were applied to elucidate whether the size of the subliminal priming (SP) effect is modulated. For SP tasks a target which requires a response is preceded by a subliminal prime, which either requires the same (congruent), or the opposite (incongruent) motor response, compared to the target. This usually leads to enhanced task performance for the congruent compared to the incongruent condition, while the differences in RTs of the incongruent minus the congruent condition denotes the SP effect.

The task conditions in the study by Fischer et al. (2007), comprised either of an accessory tone stimulus, or no-tone (used as a control condition), followed at different intervals by the presentation of a prime-target pair. For Experiment 1, a randomized presentation of tone-target intervals was applied inducing temporal uncertainty in the participants, as it was not evident at the start of the trial which preparatory interval will be presented. As a result, participants could not develop a precise temporal expectation for target onset. In contrast, for Experiment 2, a blocked presentation of preparatory intervals was applied, as a result, participant could develop a precise temporal expectation for target onset. Taken together, the comparison of the SP effect for conditions of a randomized and blocked presentation of preparatory intervals enabled the authors, to investigate whether temporal expectation and temporal preparation jointly modulate the size of the SP effect.

The results of Fischer et al. (2007) demonstrated improved task performance in the congruent compared to the incongruent condition. Furthermore, compared to the no-tone condition, the SP effect in the tone condition increased with increasing preparatory interval. In sum, these results indicated, that the tone stimulus was utilized as a temporal reference for response preparation during the preparatory intervals leading to enhanced response activation, with increasing preparatory intervals (Hackley & Valle-Inclán, 1998; Jepma et al., 2009; MÜller-Gethmann et al., 2003).

9.1.1 Temporal preparation and the utilization of reward information

Only recently, Chiew & Braver (2016), provided evidence for the assumption that adequate temporal conditions affect the interplay of reward prospect and task information (i.e. whether the upcoming trial is congruent/incongruent) leading to a modulation of cognitive control performance (Experiment 2). In their study, participants were asked to perform an Erikson flanker task, in which the reward information was either presented early, prior to the task information cue, or late, in which case, the task information was presented before the reward information. The result pattern indicated that *only* in task situations in which participants could process the reward information for a longer period (i.e. the cue presented early) in contrast to when it was presented directly before target onset, the reward prospect and task information jointly reduced interference costs; but did not jointly improve facilitation performance. The authors concluded that only with adequate temporal preparation the prospect of reward and task information could boost proactive attentional control to reduce interference costs. The evidence suggests that temporal preparation can affect the utilization of reward information, however, it remains unclear whether the interplay of temporal preparation and reward prospect can jointly facilitate task performance. In sum, there is a lack of substantial evidence of how temporal preparation affects participants capabilities to utilize reward information for performance improvements, especially in DT situations.

10. Research questions of Studies 1, 2, and 3

The aim of the present dissertation was to elucidate and specify how the prospect of reward affects DT processing in PRP DT situations, consequently, I will outline the research questions of Study 1, 2 and 3.

10.1 Research question of Study 1

For Study 1, the research question was to elucidate which processing stage(s) is (are) affected by the prospect of reward to participants task 1 performance, in the processing chain of a PRP DT situation. For that matter, the reward prospect was selectively tied to participants task 1 but not to their task 2 performance (i.e. task-selective reward association to task 1). I analyzed DT performance by applying chronometric methods to infer the locus (or loci) of the reward effect (Schubert, 1999; Schweickert, 1980). The chronometric methods and the corresponding RT predictions concerning the possible loci of the reward effect in the processing chain of task 1 and task 2 will be described within the method section of Study 1.

10.2 Research question of Study 2

For Study 2, the prospect of reward was selectively tied to participants task 2 but not to their task 1 performance (i.e. task-selective reward association to task 2), as a result, the reward prospect was tied to the task for which the processing chain is interrupted by a central bottleneck. This raises the issue, of how participant will perceive the reward prospect to task 2 in a PRP DT situation. To investigate this issue, I analyzed DT performance by applying chronometric methods to infer the locus (or loci) of the reward effect (Schubert, 1999; Schweickert, 1980), in the processing chain of task 1 and task 2. Finally, I will present the chronometric methods and the RT predictions of the possible loci of the reward effect in the processing chain of both tasks within the method section of Study 2.

As a related aim of Study 1 and 2, I aimed to provide clearer evidence for the PRP DT conditions for which reward-related performance transmissions between tasks will emerge, as previous results indicated, the absence of reward-related processing improvements on the task 2 processing time (Rieger et al., 2021; Yildiz et al., 2013). Consequently, this raises the issue, of whether reward-related processing improvements can be transmitted via the bottleneck mechanism between tasks.

10.3 Research question of Study 3

For Study 3, the first research question was, whether participants can flexibly switch their reward processing strategy, to utilize a trial-wise reward prospect, tied to their task 1 performance, to improve their DT performance. For the second research question, I investigated the temporal dynamics of reward utilization, to elucidate the relation of reward- and preparation-related processing improvements. For that matter, I analyzed whether the size of the reward effect is modulated by the length of preparatory intervals in PRP DT situations.

In the next chapters 11-13, I will give a summary of Study 1-3 and will present the relevant methods and describe the derived hypotheses.

11. Study 1: On the localization of reward effects in overlapping dual tasks

In Experiment 1, I investigated the locus of the reward effect, in the processing chain of task 1 and task 2, for selectively rewarding participants task 1 performance. In Experiment 2, I elucidated the reward-related transmission effects between task 1 and task 2, in more detail (please refer to Appendix A).

11.1 Method and Hypotheses

For both experiments, I combined a three-choice auditory tone discrimination task (250 Hz, 500 Hz or 1000 Hz) and a three-choice visual digit discrimination task (1, 5 or 9). While for Experiment 1 three SOAs (100 ms, 300 ms or 900 ms) were inserted between tasks, for Experiment 2, four SOAs (50 ms, 150 ms, 300 ms or 900 ms) were utilized. To further elucidate reward effect transmission between tasks, I applied a difficulty manipulation of the response selection of task 2, resulting in an easy and hard task condition, in Experiment 2.

For both experiments, a block-wise, task-selective reward association to task 1 performance was applied. In particular, participants received a standardized instruction that they could earn a monetary reward of 72 Euro Cent per block, if their task 1 performance was fast and accurate, while minding a low error rate on their task 2 performance. This instruction was repeated prior to each reward block. After each block, participants received feedback about their mean RT1 and percentage of correct trials, and for reward blocks, whether they earned a reward or not (and how much reward they had earned so far).

The individual performance thresholds for obtaining a reward were calculated based on mean RT1 and mean error performance of the reward blocks for each participant. The performance measures were compared to the individual performance thresholds, to decide whether or not, participant would receive a reward for their performance in the reward block. If none of their performance measures were below the individual performance thresholds participants received no reward. If either their mean RT1 or their accuracy was below their individual performance thresholds participants were rewarded (for further details please refer to Appendix A).

To investigate how the prospect of reward to task 1 affects DT processing, I utilized the effect propagation logic and the locus-of-slack method which are chronometric methods applicable for the localisation of an experimental manipulation in the processing chain of PRP DT situations (Janczyk et al., 2019; Pashler & Johnston, 1989; Schubert, 1999; Schweickert, 1978, 1980; Van Selst et al., 1999; Van Selst & Jolicoeur, 1997). Consequently both methods were applied to investigate the locus of the reward effect, for a reward prospect to task 1 performance, in the processing chain of task 1 and task 2.

In Experiment 1, I assumed a reduction of RTs in the reward compared to the no reward condition (e.g. Chiew & Braver, 2016). As a result, several possibilities are conceivable of how the prospect of reward improves task 1 processing. In detail, the effect propagation logic predicts that a change in the processing time of the pre- and/or bottleneck stages of task 1 (i.e. the perceptual stage and/or the response selection stage) of a PRP DT situation will be propagated via the bottleneck mechanism onto the task 2 processing chain affecting RT2 as well. As a result, the RT effect on task 2, is predicted to be larger at short compared to long SOA, since the lacking bottleneck mechanism at long SOA prevents that the change in task 1 processing time will be transmitted onto the processing chain of task 2.

As previously discussed, reward-related processing improvements on the perceptual and the response selection stage have been reported in sensory-motor RT tasks (Etzel et al., 2016; e.g. Kiss et al., 2009). Therefore, it is conceivable that the prospect of reward to task 1 performance shortens the pre- and/or bottleneck stages of task 1 (see Figure 11.1). This would result in a reduced RT1 in the reward compared to the no reward condition. Consequently, the reward-related processing improvements of the processing stages before or/at the bottleneck of task 1, would be propagated via the bottleneck mechanism onto the processing chain of task 2, reducing RT2. In contrast, for longer SOAs, no bottleneck between tasks emerges, over which the reward-related processing improvements can be transmitted. Consequently, this would result in larger reward effects on RT2 for short compared to long SOAs. Accordingly, a reward effect locus on the pre- and/or bottleneck stages of task 1, would result in a main effect of reward on RT1 and an overadditive interaction of reward and SOA on RT2, with larger reward effects at short compared to long SOA.

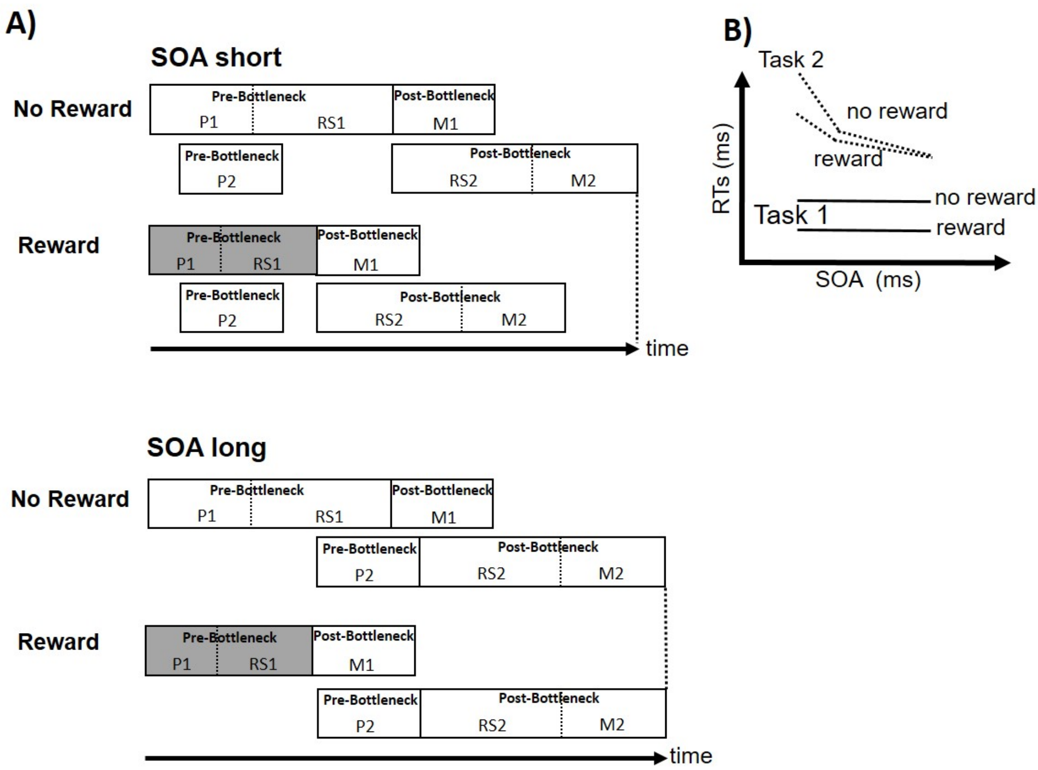

Figure 11.1: Depicted in A), the gray shaded areas of task 1 indicate that reward shortens the pre- and/or bottleneck stages of task 1. As depicted in B), this results in a shorter reaction time (RT) to task 1, in the reward compared to the no reward condition. Accompanied by a larger reward effect on the RT of task 2 for short compared to long stimulus-onset asynchrony (SOA). Pre-Bottleneck stage of task 1 comprises: P1 = perception stage of task 1; Bottleneck stage of task 1 comprises: RS1 = response selection of task 1; Post-Bottleneck stage of task 1 comprises: M1 = Motor stage of task 1; Pre-Bottleneck stage of task 2 comprises: P2 = perception stage of task 2; Bottleneck stage of task 2 comprises: RS2 = response selection stage of task 2; Post-Bottleneck stage of task 2 comprises: M2 = motor stage of task 2; Black arrow = arrow of time.

However, previous evidence also indicated that the prospect of reward can improve motor-related processing in sensory-motor RT tasks (e.g. Bundt et al., 2016), as a result, it is conceivable that the prospect of reward to task 1 performance shortens the post-bottleneck stage of task 1 (i.e. the motor stage) in a PRP DT situation (see Figure 11.2). According to the effect propagation logic, a reduction of the processing time of the post-bottleneck stage of task 1, leads to a reduction of task 1 processing time. However, since the processing time reduction of task 1 occurs *after* the central bottleneck, the processing time reduction of task 1 will not be transmitted onto the task 2 processing chain of a

PRP DT situation.

Consequently, if the prospect of reward was entirely localized on the post-bottleneck stage of task 1 shortening the motor-related processing time, this would lead to a reduced RT1 in the reward compared to the no reward condition. However, as the reward effect emerges after the central bottleneck, the reward-related processing improvements of the post-bottleneck stage of task 1, would *not* be transmitted via the central bottleneck mechanism onto the processing chain of task 2. As a result, the processing time of task 2 would be unaffected by a reward effect locus on the post-bottleneck stage of task 1. Accordingly, a reward effect locus on the post-bottleneck stage of task 1 would result in a reduction of RT1 in the reward compared to the no reward condition.

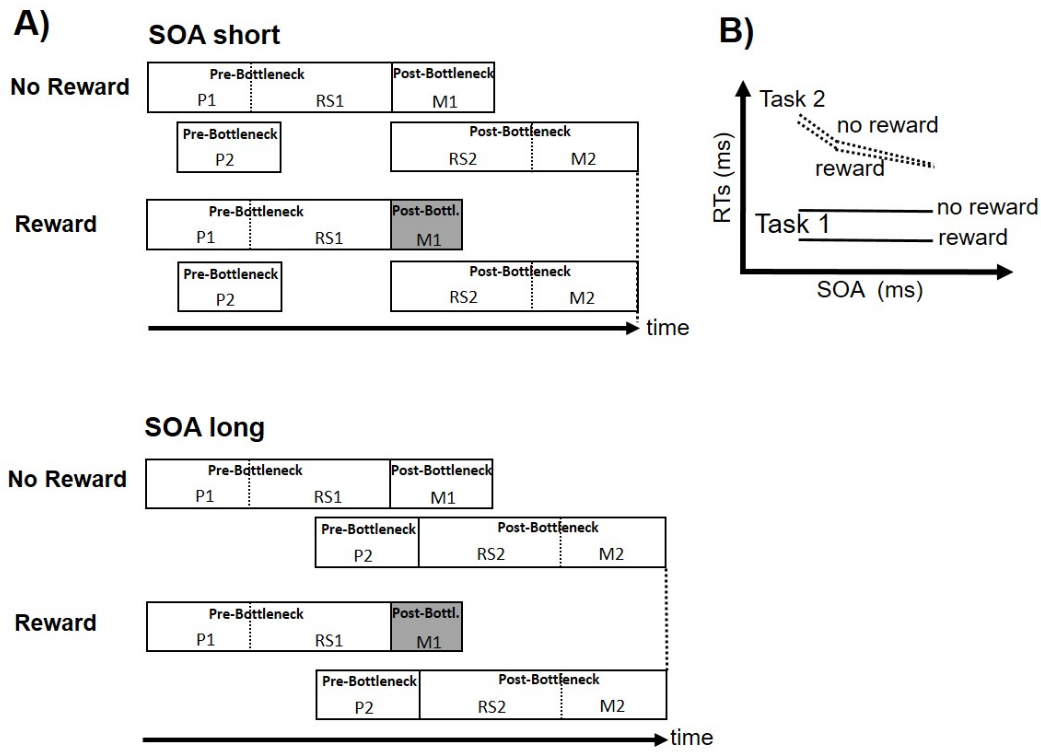

Figure 11.2: Depicted in A), the gray shaded area of task 1 indicate that reward shortens the post-bottleneck stage of task 1. As depicted in B), this only results in a shorter reaction time (RT) to task 1, in the reward compared to the no reward condition. SOA = stimulus-onset asychrony; Pre-Bottleneck stage of task 1 comprises: P1 = perception stage of task 1; Bottleneck stage of task 1 comprises: RS1 = response selection of task 1; Post-Bottleneck stage of task 1 comprises: M1 = Motor stage of task 1; Pre-Bottleneck stage of task 2 comprises: P2 = perception stage of task 2; Bottleneck stage of task 2 comprises: RS2 = response selection stage of task 2; Post-Bottleneck stage of task 2 comprises: M2 = motor stage of task 2; Black arrow = arrow of time.

Finally, as a third alternative, it is conceivable that the prospect of reward to task 1 performance affects the pre- and/or bottleneck stages *and* the post-bottleneck stage of task 1. This outcome is conceivable since previous evidence indicated task conditions in which the prospect of reward can affect each of the processing stages in a sensory-motor RT task (e.g Bundt et al., 2016; Chiew & Braver, 2016; Etzel et al., 2016; Kiss et al., 2009). As a result, the effect propagation logic predicts an RT pattern that would be indicated by a combination of the previously described RT patterns: larger reward effects on RT2 at short compared to long SOA due to effect propagation, as well as larger reward effects on RT1 compared to RT2 (see Figure 11.3). Consequently, according to the effect propagation logic, the latter RT pattern emerges, as the processing time reduction that is localized on the post-bottleneck stage of task 1 will not be transmitted onto the task 2 processing chain. As a result, a larger effect on task 1 processing time compared to task 2 processing time emerges. Consequently, such an RT pattern would indicate that some proportion of the reward effect would be located at the post-bottlenecks stage of task 1.

If the prospect of reward shortened pre- and/or bottleneck and the post-bottleneck stages of task 1, then this would lead to a reduction of RT1 in the reward compared to the no reward condition. Consequently, at short SOA, the reward-related processing time reduction of the pre- and/or bottleneck stages of task 1 would be transmitted onto the processing chain of task 2, reducing RT2. In contrast, for long SOAs, no bottleneck emerges between tasks, as a result, the reward-related processing improvements are not transmitted onto the processing chain of task 2. In addition, the reward effect localized onto the post-bottleneck stage of task 1, would further increase the reward effect on task 1 compared to task 2 processing time. As the reward-related processing time reduction of the post-bottleneck stage of task 1 occurs after the central bottleneck, the reward effect is not transmitted onto the processing chain of task 2. Accordingly, a reward effect locus on the pre- and/or bottleneck *and* the post-bottleneck stage of task 1, would result in a larger reward effect on task 1 compared to task 2, and larger reward effects on task 2 for short compared to long SOAs.

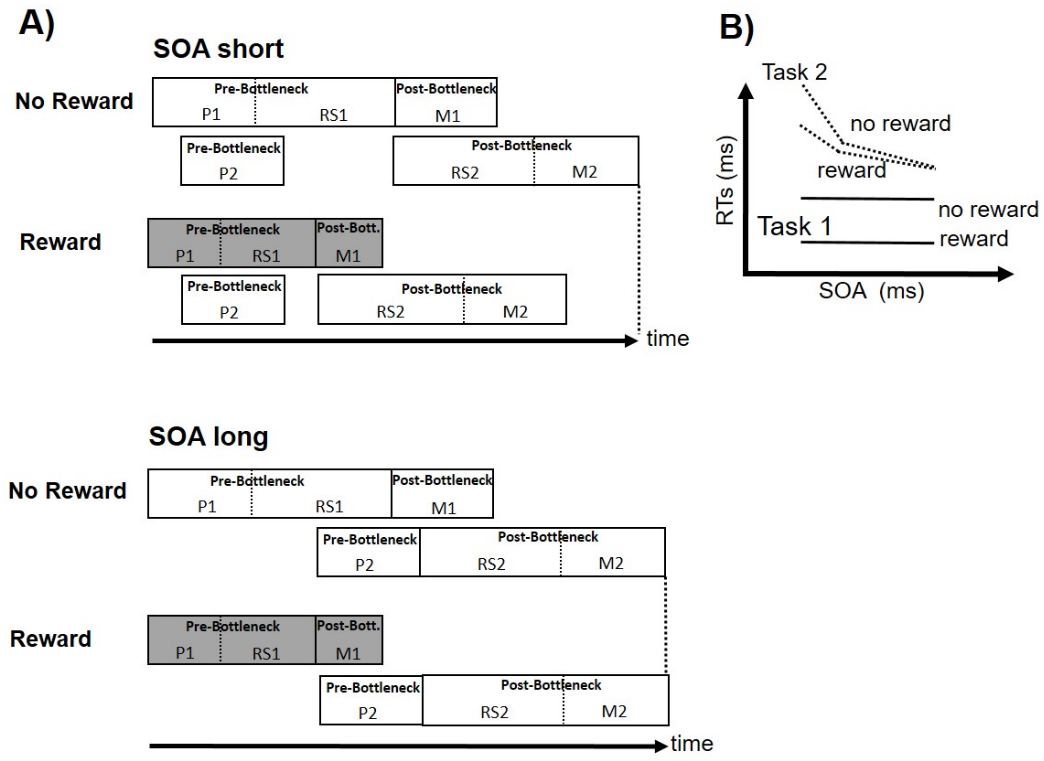

Figure 11.3: Depicted in A), the gray shaded areas of task 1 indicate that reward shortens the pre-bottleneck and/or bottleneck stages and the post-bottleneck stage of task 1. As depicted in B), this results in a shorter reaction time (RT) to task 1, in the reward compared to the no reward condition. Accompanied by a larger reward effect on the RT of task 2 for short compared to long stimulus-onset asynchrony (SOA); while the reward effect on task 1 is larger compared to task 2. Pre-Bottleneck stage of task 1 comprises: P1 = perception stage of task 1; Bottleneck stage of task 1 comprises: RS1 = response selection of task 1; Post-Bottleneck stage of task 1 comprises: M1 = Motor stage of task 1; Pre-Bottleneck stage of task 2 comprises: P2 = perception stage of task 2; Bottleneck stage of task 2 comprises: RS2 = response selection stage of task 2; Post-Bottleneck stage of task 2 comprises: M2 = motor stage of task 2; Black arrow = arrow of time.

For Experiment 2, I investigated which processing stage of task 2 was processed earlier due to the reward prospect to task 1. As there is an ongoing discussion, on whether the processing chain of task 2 is interrupted at the response selection or motor stage, the reward-related processing improvements from task 1 could propagate onto the task 2 processing chain via different target processing stages. In particular, under the assumption of a central bottleneck (e.g. Pashler, 1984), the reward-related processing improvements of task 1 would lead to an earlier onset of the response selection stage of task 2; whereas accounts assuming a peripheral bottleneck (e.g. Meyer & Kieras, 1997) would predict an earlier onset of the motor stage of task 2, which would not affect the start of the response selection process.

For the purpose of investigating whether the effect propagation from task 1 led to an earlier onset of the response selection or the motor stage of task 2, I localized the bottleneck in the processing chain of task 1 and task 2, while I also applied a reward prospect to task 1 performance. To localize the bottleneck, I added a difficulty manipulation of the response selection stage of task 2, by applying a compatible (easy) and an incompatible (hard) stimulus-response mapping. The joint application of the effect propagation and locus-of-slack methods, enables to elucidate whether the prospect of reward to task 1 led to an earlier onset of the central or peripheral stages of task 2 (Janczyk et al., 2019; Johnston & McCann, 2006; McCann & Johnston, 1992; Pashler & Johnston, 1989; Schubert, 1999; Schubert et al., 2008).

To assess, whether the processing chain of task 2 is interrupted by a bottleneck at the response selection stage, the RT2 pattern can be considered. Consequently, the additional processing time required in the hard compared to the easy condition is added *after* the central bottleneck stage for short and long SOAs leading to a prolongation of RT2. As depicted in Figure 11.4, this leads to an additive RT2 pattern between the difficulty and the SOA manipulation. For the predicted reward-related DT improvements, I expected to replicate the findings of Experiment 1.

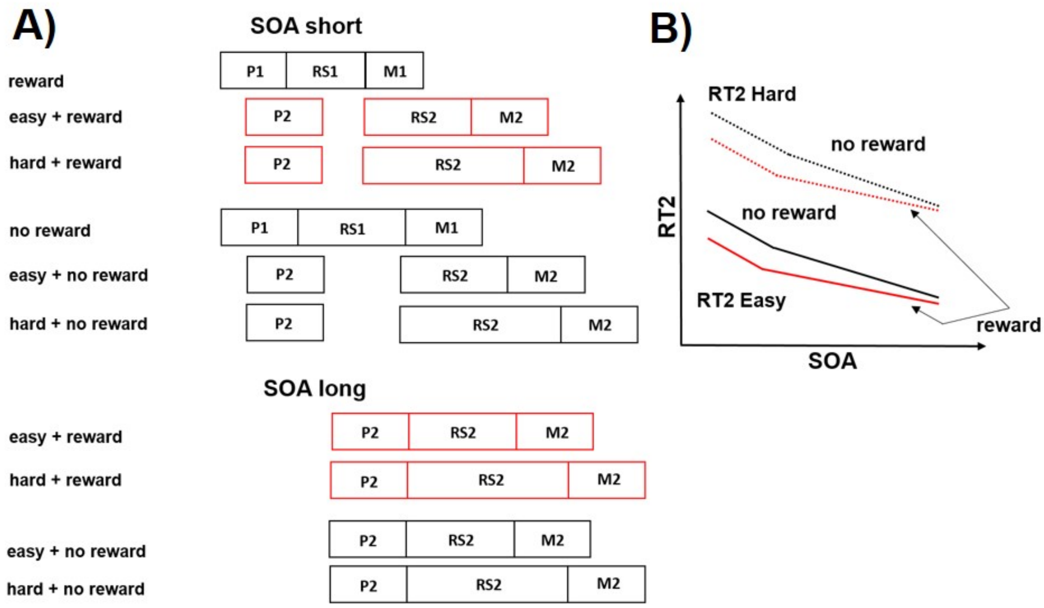

Figure 11.4: In A) is depicted, the response selection bottleneck model including reward influencing the pre- and/or bottleneck stages and the post-bottleneck stage of task 1 in the reward compared to the no reward condition. Furthermore, the difficulty manipulation of the response selection stage of task 2, is shown, resulting in easy and hard conditions. In B) are depicted, the reaction time of task 2 (RT2) predictions for the corresponding conditions illustrated in A). Additive effects of the difficulty manipulation and stimulus-onset asychrony (SOA) on RT2 should emerge, if the response selection stages of both tasks are processed serially, favoring the response selection bottleneck model. Easy = rule-based stimulus-response mapping; Hard = arbitrary stimulus-response mapping; Red indicates the rewarded conditions at short and long SOA respectively; P1 = perception stage of task 1; RS1 = response selection stage of task 1; M1 = Motor stage of task 1; P2 = perception stage of task 2; RS2 = response selection stage of task 2; M2 = motor stage of task 2.

In contrast, the processing chain of task 1 and task 2 could also be interrupted at the peripheral motor stages (Meyer & Kieras, 1997); how would that affect RT2? For that case, the increased processing time in the hard in contrast to the easy condition is absorbed into the slack emerging before the motor stage of task 2 at short in contrast to long SOA. Consequently, RT2 should be increased at long SOA in the hard compared to the easy condition, as no slack time emerges. As depicted in Figure 11.5. this results in an underadditive interaction on RT2 between the difficulty and the SOA manipulation. For the reward effects I expected to replicate the reward-related DT improvements of Experiment 1.

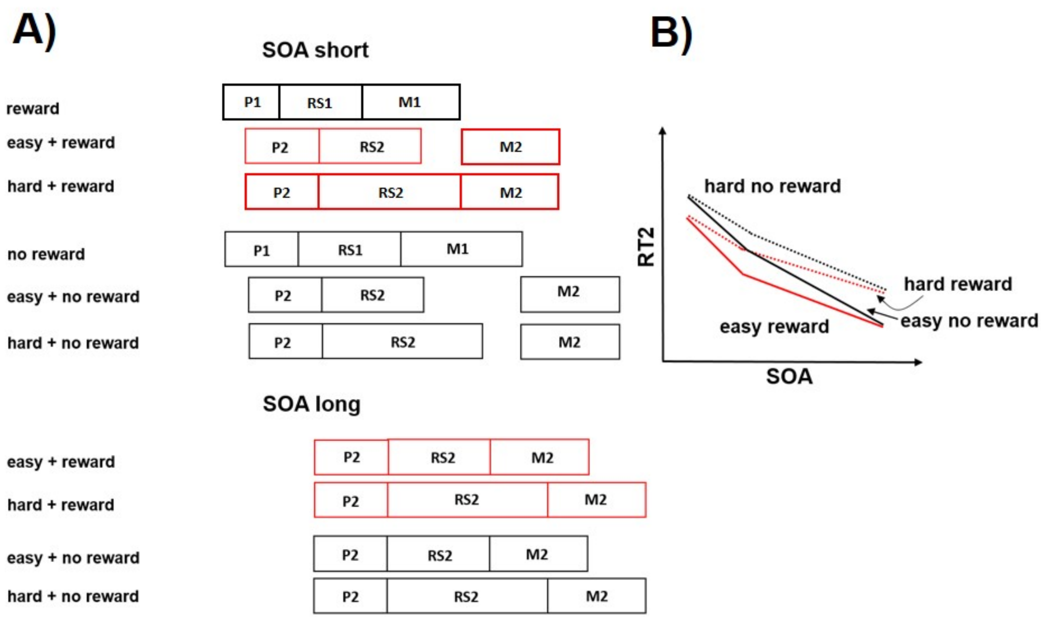

Figure 11.5: In A) is depicted, the response initiation bottleneck model including reward influencing the pre- and/or bottleneck and the post-bottleneck stages of task 1 in the reward compared to the no reward condition. Furthermore, the task difficulty manipulation of the response selection stage of task 2, is shown, resulting in easy and hard conditions. In B) are depicted, the reaction time of task 2 (RT2) predictions for the corresponding conditions illustrated in A). Underadditive effects of the task difficulty manipulation and stimulus-onset asynchrony (SOA) on RT2 should emerge if the response selection stages of both tasks are processed concurrently, favoring the response initiation bottleneck model. Easy = rule-based stimulus-response mapping; Hard = arbitrary stimulus-response mapping; Red indicates the rewarded conditions at short and long SOA respectively; P1 = perception stage of task 1; RS1 = response selection stage of task 1; M1 = Motor stage of task 1; P2 = perception stage of task 2; RS2 = response selection stage of task 2; M2 = motor stage of task 2.

11.2 Results and Discussion

For Experiment 1, the result pattern revealed a main effect of reward on RT1 (see Figure 11.6). Participants responded faster in the reward (m = 690 ms) compared to the no reward condition (m = 726 ms) to task 1. Most importantly for the issue of reward effect localization, an overadditive interaction of reward and SOA on RT2 was obtained with larger reward-related task 2 improvements for SOA 100 (m = 27 ms) compared to SOA 900 (m = -2 ms). Taken together these results indicate that at short SOA the reward-related task 1 improvements were transmitted onto the task 2 processing chain reducing also RT2. This effect pattern is consistent with the assumption that the task-selective reward association to task 1 shortened the pre- and/or bottleneck stages of task 1.

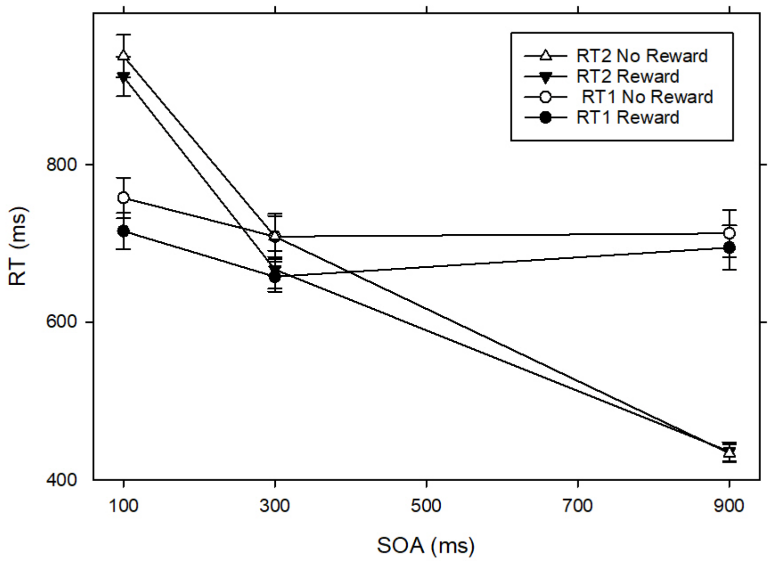

Figure 11.6: Mean reaction time (RT) of task 1 (RT1) and task 2 (RT2) as a function of stimulus-onset asychrony (SOA) and reward for Experiment 1. Error bars represent the standard error of the mean

Importantly, for the issue of whether the reward prospect affected the motor processes of task 1 *in addition* to the pre-motoric effects, further tests showed that for each SOA level the reward-related task 1 improvements were increased compared to task 2. This finding indicates that the reward prospect affected the motor stage of task 1 in addition to the pre-motoric reward effects. While the reward-related task 1 improvements of the pre- and/or bottleneck stages of task 1 were transmitted via the bottleneck mechanism onto the task 2 processing chain, the reward effect on the motor stage of task 1 was not transmitted to task 2, therefore increasing the reward-related task 1 improvements in comparison to task 2.

For Experiment 2, the reward-related task 1 and task 2 improvements from Experiment 1 were replicated. Most importantly, for the issue of the bottleneck localization, a main effect of task difficulty on RT2 was obtained. The RT2 in the easy (m = 825 ms) condition was shortened compared to the hard (m = 1028 ms) condition (see Figure 11.7), while the interaction of task difficulty and SOA did not reach significance. Both results are consistent with the assumption that task difficulty and SOA affected RT2 in an additive fashion, which speaks against the assumption of a bottleneck emerging at the peripheral motor stages. These results favor instead the conclusion of a response selection bottleneck emerging at the central stages. As a result, this effect pattern indicates that the response selection stages were processed serially, however, the response selection of task 2 in the reward in contrast to the no reward condition was processed earlier due to the reward prospect to task 1.

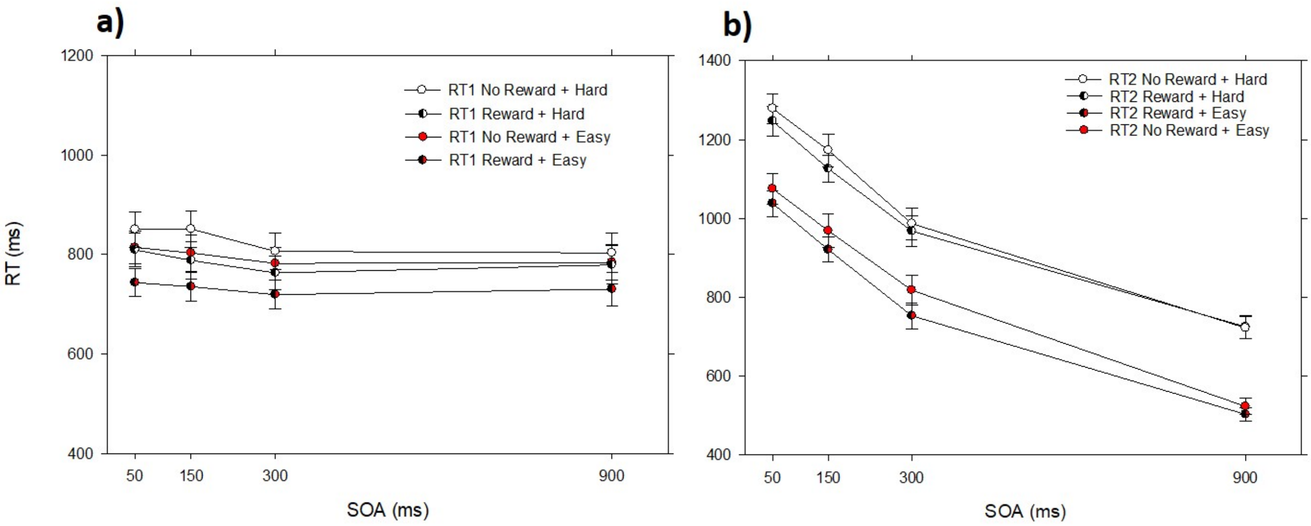

Figure 11.7: Mean reaction time (RT) of task 1 (RT1) and task 2 (RT2) as a function of stimulus-onset asynchrony (SOA), reward, and task difficulty for Experiment 2. Panel a) depicts task 1 performance and panel b) depicts task 2 performance. Error bars represent the standard error of the mean.

To summarize the results, Experiment 1 and 2 provided evidence for the assumption that the task-selective reward association to task 1 resulted in effect propagation over the response selection bottleneck from the rewarded task 1 onto the nonrewarded task 2, resulting in an earlier onset of the response selection of task 2. Therefore the effect propagation logic can be utilized for the interpretation of reward-related transmission effects between task 1 and task 2. While the prospect of reward improved RT1 and RT2, the serial processing of the response selection stages was not affected. Finally, the reward effect was increased for the reward associated task 1 compared to task 2, indicating that parts of the reward effect affected motor processes of task 1.

To discuss the results of Study 1, the results suggests that the task-selective reward association to task 1 resulted in improved task 1 and task 2 performance. The chronometric analysis revealed that especially pre-motoric (and motor-related) processing stages of task 1 were shortened by the prospect of reward thereby extending previous evidence on how the prospect of reward affects task performance in sensory-motor RT tasks (Engelmann, 2009; Hübner & Schlösser, 2010; Kiss et al., 2009; Krebs et al., 2011; Krebs & Woldorff, 2017). As a result, at short SOA, the prospect of reward to task 1, led to an earlier onset of the response selection stage of task 2, thereby reducing RT2. In contrast for the long SOA condition no bottleneck emerges over which the reward effects can be transmitted. This effect pattern demonstrates for which DT conditions reward-related transmission effects between tasks emerge extending previous results (Rieger et al., 2021). Finally, the results suggest that the prospect of reward improved RT1 and RT2 performance, however, this resulted not in improved parallel processing of the response selection stages as had been suggested by proponents of a strategical bottleneck model for task conditions of reward prospect (Meyer & Kieras, 1997; Salvucci & Taatgen, 2008). I will address these points in more detail in the General Discussion section of this dissertation in Chapter 14.

12. Study 2: Investigation of reward effects in overlapping dual-task situations

In Experiment 1, I investigated, how participants will perceive a reward prospect, tied to task 2 performance, for which the processing chain is interrupted by a central bottleneck, in a PRP DT situation. In Experiment 2, I elucidated onto which processing stage of task 2 the reward-related processing improvements of task 1 propagated (please refer to Appendix B).

12.1 Method and Hypotheses

Across both experiments, I combined a three-choice auditory tone discrimination task (250 Hz, 500 Hz or 1000 Hz) and a three-choice visual digit discrimination task (1, 5 or 9), for Experiment 1 separated by three SOAs (100 ms, 300 ms or 900 ms), while for Experiment 2 tasks were separated by four SOAs (50 ms, 150 ms, 300 ms or 900 ms). Furthermore, I applied a difficulty manipulation of the response selection of task 2, resulting in an easy and hard response mapping, for the investigation of between task propagation effects, in

Experiment 2.

For both experiments, a block-wise, task-selective reward association to task 2 performance was applied. Participants received a standardized instruction that they could earn a monetary reward of 72 Euro Cent per block, if their task 2 performance was fast and accurate, while minding a low error rate on task 1 performance. This instruction was repeated prior to each reward block. After each block, participants received feedback about their mean RT2, percentage of correct trials, and for reward blocks, whether they earned a reward or not (and how much reward they had earned so far).

The computation of the individual performance thresholds for obtaining a reward were identical to Study 1, with the exception that task 2 performance measures were compared against individual performance thresholds to decide whether or not a participant would receive a reward (for further details please refer to Appendix B).

To investigate, how DT processing is affected by a reward prospect tied to task 2 performance, I employed the effect propagation and locus of slack logics, which are chronometric methods applicable for the localization of an experimental manipulation in the processing chain of task 1 and task 2 (Pashler, 1994; Schubert, 1999; Schweickert, 1978, 1980). Consequently, both methods were applied to investigate the locus of the reward effect in the processing chain of task 1 and task 2, assuming, based on previous evidence, that the prospect of reward to task 2 performance will shorten RTs in the reward compared to the no reward condition (e.g. Chiew & Braver, 2016).

For Experiment 1, the reward prospect to task 2, raises the issue of how participants will perceive the reward prospect. Lets first consider the case, in which the prospect of reward to task 2 selectively affects task 2 processing. According to the locus-of-slack logic, any effect on the processing duration of the pre-bottleneck stage of task 2 (i.e. the perceptual stage of task 2), prior to the bottleneck stage, will be absorbed into the slack at short SOAs. In contrast, for longer SOAs, no slack time emerges, and as a result, a processing time reduction of the pre-bottleneck stage of task 2 will lead to an earlier onset of the subsequent task 2 processing stages, i.e. the response selection and motor stages, affecting RT2.

Based on previous evidence it is conceivable that perceptual processing of task 2 is improved by the prospect of reward (Engelmann & Pessoa, 2007; Kiss et al., 2009). As a result, the prospect of reward to task 2 could shorten the pre-bottleneck stage of task 2 (see Figure 12.1). For short SOA conditions, a reward-related reduction of the processing time of the pre-bottleneck stage of task 2, would be absorbed into slack emerging prior to the bottleneck stage. In contrast, for longer SOAs, no slack time emerges, as a result, the reward-related processing time reduction of the pre-bottleneck stage of task 2, would lead to an earlier onset of the bottleneck and post-bottleneck stages of task 2, reducing RT2. Consequently, a reward effect locus on the pre-bottleneck stage of task 2 would result in an underadditive interaction of reward and SOA on RT2, with larger reward effects at long compared to short SOA.

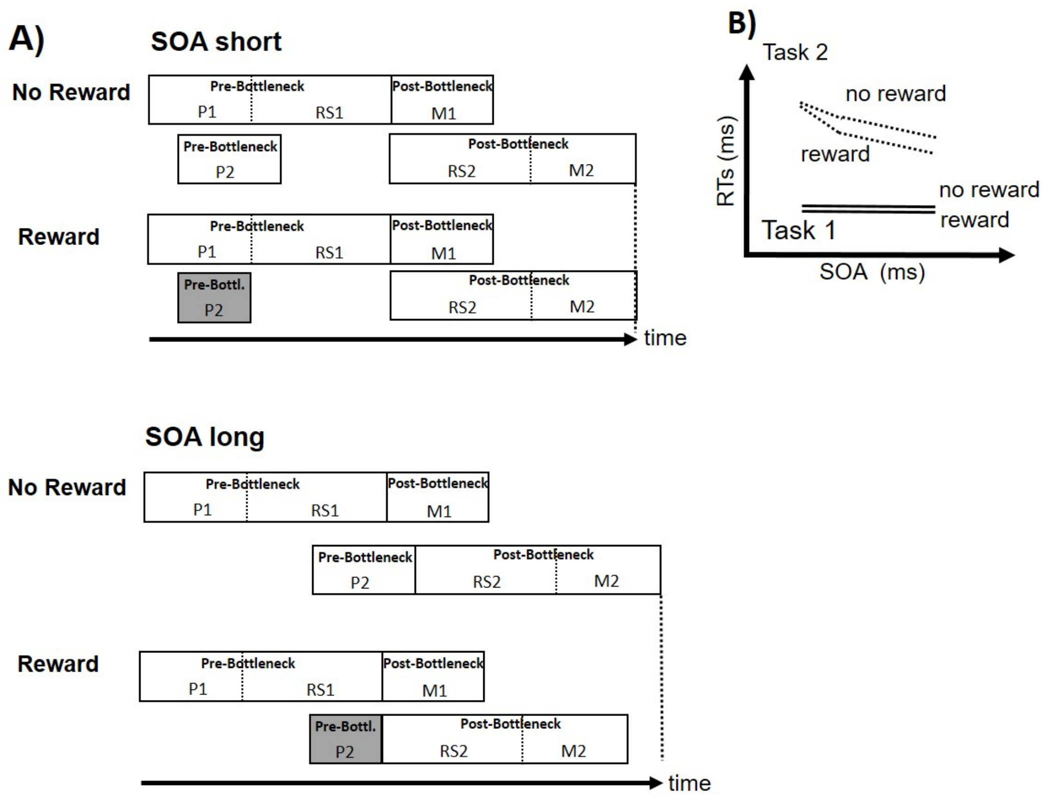

Figure 12.1: Depicted in A), the gray shaded area of task 2 indicates that reward shortens the pre-bottleneck stage of task 2. As depicted in B), this only results in a larger reward effect at long stimulus-onset asynchrony (SOA) compared to short SOA, on the reaction time (RT) of task 2. Pre-Bottleneck stage of task 1 comprises: P1 = perception stage of task 1; Bottleneck stage of task 1 comprises: RS1 = response selection of task 1; Post-Bottleneck stage of task 1 comprises: M1 = Motor stage of task 1; Pre-Bottleneck stage of task 2 comprises: P2 = perception stage of task 2; Bottleneck stage of task 2 comprises: RS2 = response selection stage of task 2; Post-Bottleneck stage of task 2 comprises: M2 = motor stage of task 2; Black arrow = arrow of time.

In contrast, previous evidence indicated that response selection and motor-related processing can be improved by a reward prospect (Bundt et al., 2016; Chiew & Braver, 2016; Etzel et al., 2016). As a result, it is conceivable that the prospect of reward to participants task 2 performance shortens the bottleneck and/or post-bottleneck stage of task 2 (i.e. the response selection and/or the motor stage/s) (see Figure 12.2). According to the locus-of-slack logic, a processing time reduction of the bottleneck and/or post-bottleneck stages of task 2 will result in a processing time reduction of task 2 for short and long SOAs.

Consequently, if the prospect of reward to task 2, shortens the bottleneck and/or post-bottleneck stages of task 2, then this should lead to a reduction of the task 2 processing time, for short and long SOAs. Accordingly, such a reward effect locus would result in a reduced RT2 in the reward compared to the no reward condition for all SOA levels.

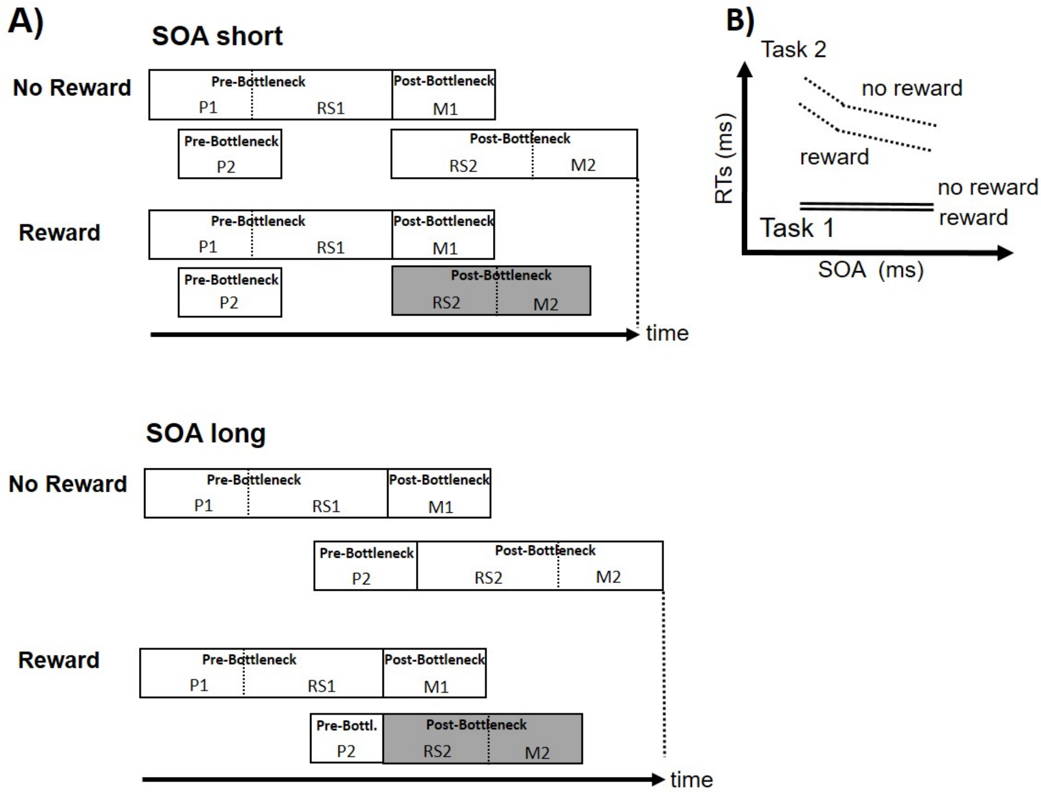

Figure 12.2: Depicted in A), the gray shaded areas of task 2 indicate that reward shortens the bottleneck and/or the post-bottlneck stages of task 2. As depicted in B), this only results in reward effects at short and long stimulus-onset-asychrony (SOA) on the reaction time (RT) of task 2. Pre-Bottleneck stage of task 1 comprises: P1 = perception stage of task 1; Bottleneck stage of task 1 comprises: RS1 = response selection of task 1; Post-Bottleneck stage of task 1 comprises: M1 = Motor stage of task 1; Pre-Bottleneck stage of task 2 comprises: P2 = perception stage of task 2; Bottleneck stage of task 2 comprises: RS2 = response selection stage of task 2; Post-Bottleneck stage of task 2 comprises: M2 = motor stage of task 2; Black arrow = arrow of time.

As indicated previously, participants might not perceive the reward prospect selectively onto task 2 processing, but instead selectively onto task 1 processing. This assumption is reasonable considering the recent results of Zedelius et al. (2012), who could show that the reward prospect for a future task will result in reward-related performance improvements in an intermediate sensory-motor RT task. The authors inferred that the reward-related performance improvements emerged due to improved preparation in the reward compared to the no reward condition. These results can be related with current findings from the field investigating the task representation of DT situations. In detail, there is accumulating evidence that participants activate a higher-order DT representation at the start of the DT situation which is linked to the representation of both component tasks (Hirsch et al., 2018; Kübler et al., 2018; Schubert & Strobach, 2018). Several studies could demonstrate that participants prepare the task 1 and task 2 processing chain prior to trial onset, as a result, the reward prospect to task 2 could affect the processing chain of task 1. To elucidate whether the task-selective reward association to task 2 will affect task 1 processing, the effect propagation method was applied to test for reward effects on RT1 performance (Pashler, 1994; Schubert, 1999; Schweickert, 1978, 1980).

The potential loci of the reward effect during the task 1 processing chain have been discussed and illustrated, previously, in the method section of Study 1. For the sake of brevity, I will not repeat the rationale of the effect propagation logic and the corresponding RT patterns. Instead, I will invite the reader to refer to Chapter 11 to consult the stage models with the corresponding RT predictions for the potential loci of the reward effect in the processing chain of task 1. The corresponding figures can be found on pages, 35, 37 and 39, respectively.

For Experiment 2, I investigated explicitly the assumption of a central bottleneck from Experiment 1. In detail, the results of Experiment 1 showed that the prospect of reward to task 2 performance resulted in reward effects on task 1 performance. The effect propagation logic indicated that the locus of the reward effect was on pre- and/or bottleneck stages of task 1. As a result, the reward effect was transmitted via the central bottleneck mechanism onto the processing chain of task 2, with larger reward effects at short compared to long SOA. However, the *response initiation bottleneck model* (De Jong, 1993; Karlin & Kestenbaum, 1968; Keele, 1972) predicts an identical RT1 and RT2 pattern for a reward effect locus on pre- and/or bottleneck stages of task 1. In particular, according to this model any change in the processing duration of the pre- and/or bottleneck stages of task 1, will be propagated onto the task 2 processing chain, at short but not at long SOAs. Most importantly, however, the processing time reduction will be propagated onto the motor stage and not onto the response selection stage of task 2. As a result, this model assumes a bottleneck at the motor stage and not at the response selection stage. Therefore it is mandatory to localize the bottleneck in the processing chain of task 1 and task 2, to elucidate onto which processing stage the processing time reduction from task 1 will be transmitted. Consequently, for Experiment 2, the bottleneck was localized in the processing chain of task 1 and task 2, to infer onto which processing stage of task 2 the reward-related processing improvements propagated (Pashler, 1994; Schubert, 1999; Schweickert, 1980).

For the localization of the bottleneck within the processing chain of task 1 and task 2, I applied a difficulty manipulation of the response selection stage of task 2, resulting in an easy and hard condition, while additionally applying a prospect of reward to task 2 performance. Subsequently, the combined effects of the difficulty and SOA manipulation are interpreted with the locus-of-slack logic, to localize the bottleneck either at the response selection or the motor stages of task 1 and task 2; while the reward-related processing improvements are interpreted with the effect propagation logic (Janczyk et al., 2019; Johnston & McCann, 2006; Karlin & Kestenbaum, 1968; Keele, 1972; McCann & Johnston, 1992; Pashler & Johnston, 1989; Schubert, 1999; Schubert et al., 2008; Van Selst &

Jolicoeur, 1997). Taken together, this approach enables the investigation of whether the reward effect propagated from task 1 onto the response selection or onto the motor stage of task 2.

For the case, that the bottleneck emerges at the response selection stages, one can observe how RT2 would be affected. In that case, the additional processing time required in the hard in contrast to the easy condition is added after the bottleneck stage for short and long SOAs prolonging RT2 (see Figure 12.3). As a result, one would predict additive effects of the task difficulty manipulation and SOA on RT2, if a central bottleneck was interrupting the processing chain of task1 and task 2. With respect to the predicted reward effects, I expected to replicate the results from Experiment 1.

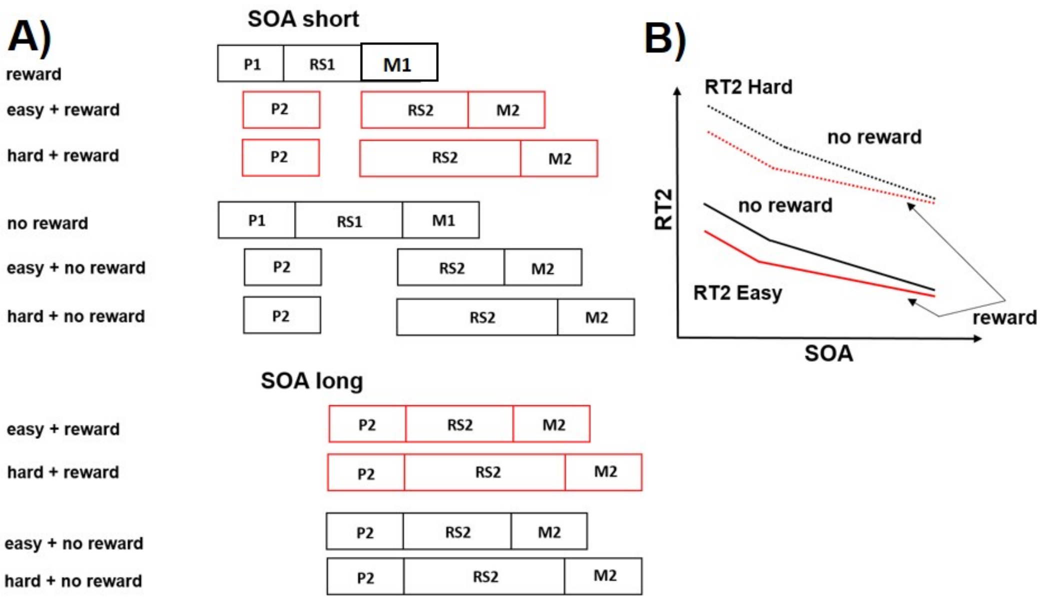

Figure 12.3: In A) is depicted, the response selection bottleneck model including reward influencing the pre- and/or bottleneck stages of task 1 in the reward compared to the no reward condition. Furthermore, the difficulty manipulation of the response selection stage of task 2, is shown, resulting in easy and hard conditions. In B) are depicted, the reaction time of task 2 (RT2) predictions for the corresponding conditions illustrated in A). Additive effects of the difficulty manipulation and stimulus-onset asychrony (SOA) on RT2 should emerge, if the response selection stages of both tasks are processed serially, favoring the response selection bottleneck model. Easy = rule-based stimulus-response mapping; Hard = arbitrary stimulus-response mapping; Red indicates the rewarded conditions at short and long SOA respectively; P1 = perception stage of task 1; RS1 = response selection stage of task 1; M1 = Motor stage of task 1; P2 = perception stage of task 2; RS2 = response selection stage of task 2; M2 = motor stage of task 2.

In contrast, how would RT2 be affected, if the bottleneck emerged at the motor stages? If that was the case, the additional processing time needed in the hard in contrast to the easy condition would be absorbed into the slack at short SOA emerging before the motor stage of task 2. In contrast, for long SOAs, the additional time required in the hard condition would increase the processing duration in contrast to the easy condition, leading to an increase in RT2 (see Figure 12.4). As a result, this would lead to an underadditive interaction of the difficulty manipulation and SOA on RT2. For the predicted reward effects, I expected to replicate the results from Experiment 1.

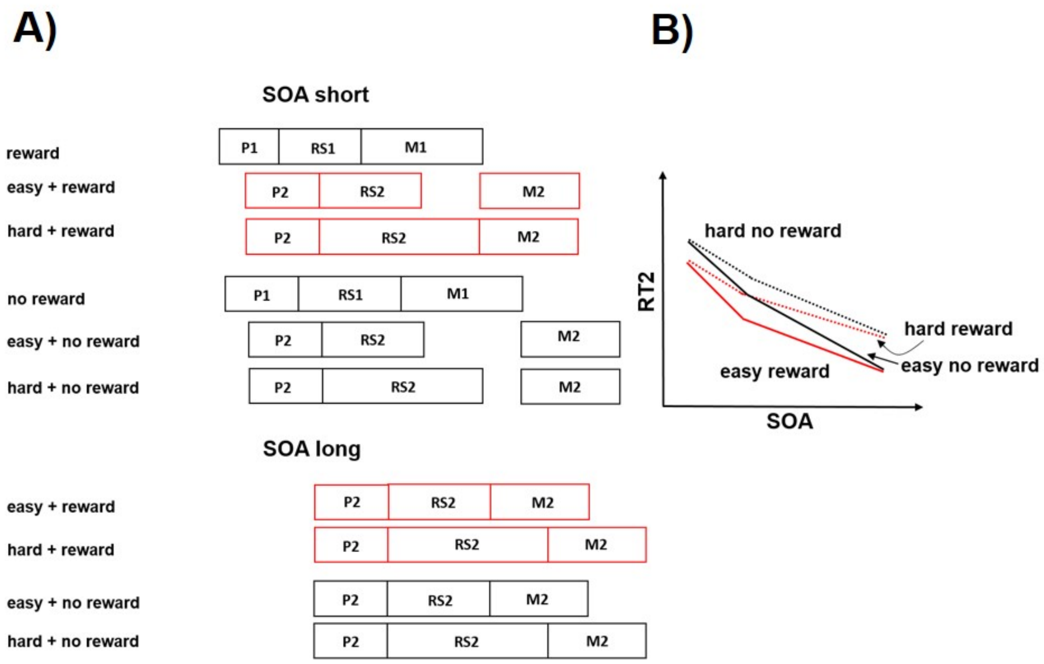

Figure 12.4: In A) is depicted, the response initiation bottleneck model including reward influencing the pre- and/or bottleneck stages of task 1 in the reward compared to the no reward condition. Furthermore, the task difficulty manipulation of the response selection stage of task 2, is shown, resulting in easy and hard conditions. In B) are depicted, the reaction time of task 2 (RT2) predictions for the corresponding conditions illustrated in A). Underadditive effects of the task difficulty manipulation and stimulus-onset asynchrony (SOA) on RT2 should emerge if the response selection stages of both tasks are processed concurrently, favoring the response initiation bottleneck model. Easy = rule-based stimulus-response mapping; Hard = arbitrary stimulus-response mapping; Red indicates the rewarded conditions at short and long SOA respectively; P1 = perception stage of task 1; RS1 = response selection stage of task 1; M1 = Motor stage of task 1; P2 = perception stage of task 2; RS2 = response selection stage of task 2; M2 = motor stage of task 2.

12.2 Results and Discussion

For Experiment 1, the result pattern indicated a main effect of reward on RT1. Participants responded faster in the reward (m = 664 ms) compared to the no reward condition (m = 698 ms). This result indicated that participants perceived the task-selective reward association to task 2 onto task 1 processing. Most importantly for the issue of localizing the reward effect, an overadditive interaction of reward and SOA on RT2 was obtained (see Figure 12.5) with larger reward effects at short (m = 51 ms) compared to long SOA (m = 21 ms). Taken together these results indicate that the prospect of reward to task 2, affected the pre- and/or bottleneck stages of task 1 reducing RT1. These findings are consistent with the assumption, that at short SOA the reward-related task 1 improvements were transmitted via the bottleneck mechanism onto the task 2 processing chain, reducing RT2, as well.

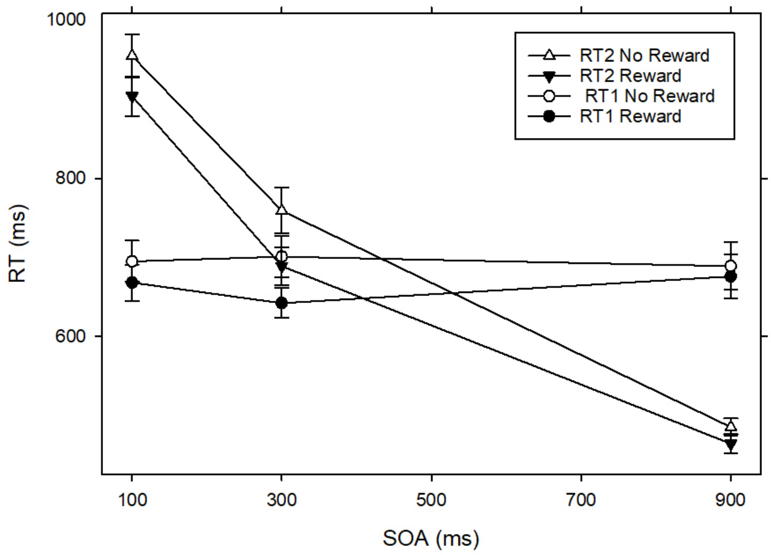

Figure 12.5: : Mean reaction time (RT) of task 1 (RT1) and task 2 (RT2) as a function of stimulus-onset asychrony (SOA) and reward for Experiment 1. Error bars represent the standard error of the mean.

Importantly, for the issue of whether the prospect of reward to task 2 affected the motor processes of task 1 *in addition*, the mean reward effect on task 2 ($m = 47$ ms) was increased compared to task 1 ($m = 34$ ms). This finding is not consistent with assumption that the reward prospect to task 2 affected the motor processes of task 1, but instead it indicates that the reward prospect to task 2 resulted in a direct reward effect on the task 2 processing chain without being transmitted from task 1.

For Experiment 2, the reward-related task 1 and task 2 improvements obtained from Experiment 1 were replicated. In addition a main effect of task difficulty on RT2 was obtained. For the easy condition RT2 ($m = 804$ ms) was reduced compared to the hard ($m = 991$ ms) condition (see Figure 12.6). Importantly, for the issue of bottleneck localization, the interaction of task difficulty and SOA did not reach significance. As a result, both findings are in line with the assumption that task difficulty and SOA affected RT2 in an additive fashion, which speaks against the assumption of a bottleneck at the response initiation stages. Instead such a result pattern favors the conclusion of a response selection bottleneck emerging at the central stages, which indicates that the reward prospect to task 2 propagated over the response selection stage of task 1 onto the response selection stage of task 2.

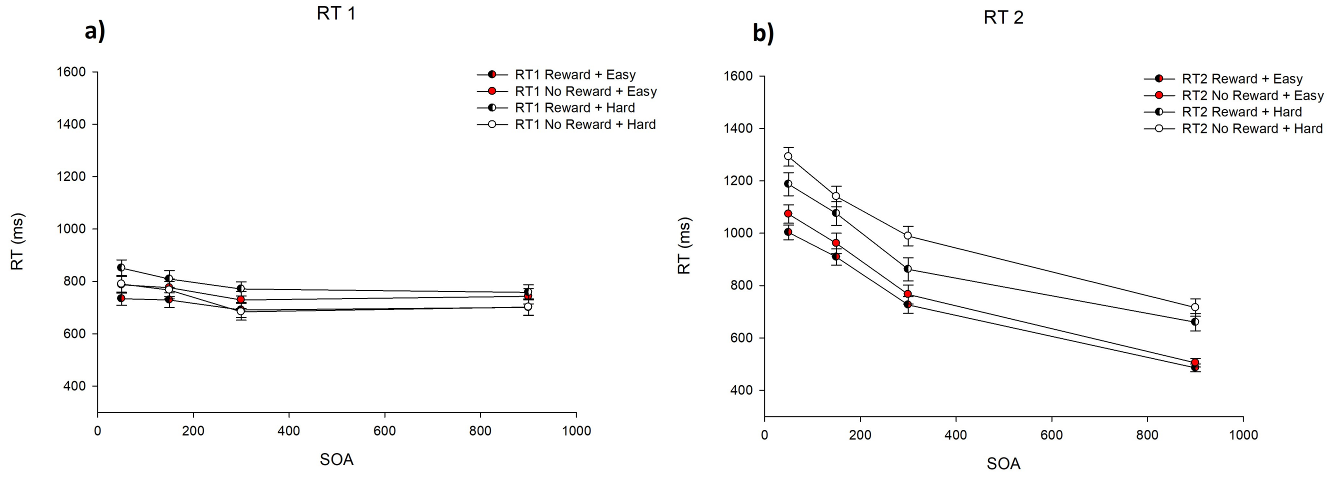

Figure 12.6: Mean reaction time (RT) of task 1 (RT1) and task 2 (RT2) as a function of stimulus-onset asynchrony (SOA), reward, and task difficulty for Experiment 2. Panel a) represents task 1 performance and panel b) represents task 2 performance. Error bars represent the standard error of the mean

To summarize the results, Experiment 1 and 2 provided evidence for the assumption that the task-selective reward association to task 2 performance improved task 1 processing. This resulted in reward-related processing improvements on pre- and/or bottleneck stages of task 1, which were propagated at short SOA via the central bottleneck mechanism onto the response selection stage of task 2, reducing RT2. Finally, the reward effect on the rewarded task 2 was increased compared to the nonrewarded task 1, indicating that the task-selective reward association to task 2 affected task 2 processes directly, which did not originate from effect propagation of task 1.

To discuss Study 2, both experiments provided evidence consistent with the assumption that the task-selective reward association to task 2 affected task 1 processing. Previous investigations suggested that participants component task representations are linked to a higher-order DT representation that is activated at the start of the DT situation (Hirsch et al., 2018; Kübler et al., 2018; Schubert & Strobach, 2018). As a result, one possibility, could be, that the task-selective reward association to task 2 did not selectively improve task 2 processing, but instead the prospect of reward could have been assigned to the DT representation starting with task 1. Consequently, this resulted in the obtained reward-related processing improvements already on the pre- and/or bottleneck stages of task 1 which were transmitted via the central bottleneck mechanism onto the task 2 processing chain, reducing also RT2. In addition, the reward effect on the rewarded task 2 was increased compared to the nonrewarded task 1. This reward size pattern could indicate that participants processed the rewarded and nonrewarded tasks, with different reward values, leading to the different reward effects. I will address these points in more detail in the General Discussion section of this dissertation in Chapter 14.

13. Study 3: On the temporal dynamics of reward utilization in dual-tasking situations

In Experiment 1, I investigated whether participants are able to flexibly switch their reward processing strategy, on a trial-to-trial basis, for a reward prospect to their task 1 performance. Furthermore, I investigated, the relation of reward- and preparation-related processing improvements. In Experiment 2, I tested whether temporal expectation modulated the temporal dynamics of reward utilization (please refer to Appendix C).

13.1 Method and Hypotheses

Across both experiments, the task situation consisted of a three-choice auditory tone discrimination task (250 Hz, 500 Hz or 1000 Hz) and a three-choice visual digit discrimination task (1, 5 or 9), which were separated by one of three SOAs (100 ms, 300 ms, or 900 ms). Prior to tone onset, either 200 ms or 700 ms, a cue was presented, signaling, whether the upcoming trial would be reward-relevant or not. The presentation of cue-target intervals (CTI) was applied block-wise for Experiment 1 and randomized for Experiment 2.

For both experiments, a trial-wise, task-selective reward association to task 1 performance was applied. Participants were instructed that they could earn a monetary reward of 72 Euro Cent per block, if their response to task 1 was fast and accurate while maintaining low error rates in task 2. After each block, participants received feedback about their mean RT1, percentage of correct trials, and whether they earned a reward or not (and how much reward they had earned so far). The individual threshold computations for obtaining a reward were identical to Study 1 (please refer to Appendix C for details).

For the first research aim of Experiment 1, I investigated whether participants are able to flexibly switch their reward processing strategy between trials, while their task 1 performance was rewarded. As a consequence of the trial-wise reward prospect, cue identity (i.e. signaling either reward or no reward trial) varied randomly from trial to trial, as a result participants were required to adjust their reward processing strategy between trials as well, in order to obtain a reward.

Consequently, I assumed, that if participants could flexibly switch their reward processing strategy between trials, then this should result in an RT1 and RT2 pattern, that had been previously obtained, by applying a block-wise reward prospect. Accordingly, I predicted a shortened RT1 in the reward compared to the no reward condition, as well as larger reward effects at short compared to long SOA on RT2. According to the effect propagation logic such an RT pattern emerges, if the processing stages before or/at the bottleneck of task 1 are shortened leading to a reduction of RT1. As a result, at short in contrast to long SOAs, the change in the processing duration of task 1 will be propagated via the bottleneck mechanism onto the processing chain of task 2, reducing RT2 (Pashler, 1994; Schubert, 1999; Schweickert, 1978). Consequently, the effects on RT2 should be increased for short compared to long SOA, as the lack of a bottleneck prevents the transmission of RT changes from task 1 onto task 2. The emergence of such an RT1 and RT2 pattern would suggest, that participants flexibly switched their reward processing strategy between trials.

For the second research question, I investigated the relation of reward- and preparation-related processing improvements, by comparing the size of the reward effect on task 1 performance, for different CTIs. For each DT condition, a cue was presented indicating either a reward or no reward trial, as a result, participants could utilize the cue as a temporal reference for response preparation in each DT condition. In the reward, in contrast, to the no reward condition, the reward information could additionally improve task processing. For Experiment 1, the block-wise presentation of CTIs, led to a precise temporal expectation of task 1 onset. In contrast, for Experiment 2, the presentation of CTIs was randomly changing from trial to trial, as a result, participants could not develop a precise temporal expectation of task 1 onset. Taken together, the comparison of the reward effects for conditions of a block-wise and randomized presentation of CTIs enables the investigation of whether the temporal dynamics of reward utilization are affected by the temporal expectations of task 1 onset (e.g. Fischer et al., 2007).

On the issue, of how reward- and preparation-related processing improvements are related, two opposing outcomes are conceivable, based on previous evidence. As a first possibility, the prospect of reward could improve preparatory processes, described as a ballistic curve, within the short CTI. Such an assumption is conceivable as previous investigations reported evidence consistent with the assumption that preparatory processes can be optimized to their peak within 200-250 ms (Gottsdanker, 1980); this would fit well with the assumption that the prospect of reward improves preparatory processes, as suggested by several authors, (Bundt et al., 2016; Chiew & Braver, 2013; Kleinsorge &

Rinkenauer, 2012; Rieger et al., 2021) as a result, the following scenario is conceivable: the emergence of comparable reward-related processing improvements for short and long CTI conditions. For the current case, in each trial a cue was presented which participants could utilize as temporal reference for preparing their response. If, furthermore, the cue signaled the prospect of reward in the short CTI condition, then, this should optimize preparatory processes to their peak, for an extended period, resulting in improved DT performance in the reward compared to the no reward condition.

In contrast, the reward effect could increase with an increasing length of the CTI, reflecting an improved utilization of reward information. Such a possibility is conceivable, since Chiew & Braver (2016) demonstrated that the prospect of reward and prior task information jointly improved interference costs, only with increasing preparation time. Consequently, the authors suggested improved encoding and processing of the reward information with an increased preparation duration. In the current situation, assuming that the utilization of reward information improves *further* with an increasing CTI, then, this should result in larger reward-related processing improvements in the long compared to the short CTI condition on RTs. For the current case, in each trial a cue was presented which participants could utilize as a temporal reference for response preparation. If, furthermore, the cue signaled a reward prospect in the long CTI condition, then DT performance in the reward compared to the no reward condition should be improved to a greater extend compared to the short CTI condition.

To further investigate the temporal dynamics of reward utilization I additionally conducted a distribution analysis of RTs (Ratcliff, 1979; Schubert et al., 2002; Steinborn et al., 2017), focusing on the tails of the RT distribution. In particular, for trials with short RTs, i.e. the left tail of the RT distribution, I supposed that the cognitive processing chain is executed efficiently leaving little or no room for improvements by the prospect of reward and the CTI manipulation (De Jong, 2000). In contrast, for trials with longer RTs, i.e. the right tail of the RT distribution, I assumed that the prospect of reward can further improve the cognitive processing chain. This assumption is reasonable as previous investigations reported an effect of a mental effort manipulation on the right tail of the RT distribution, suggesting that mental effort improved attentional mobilization (Falkenstein et al., 2003; Kleinsorge, 2001). For the scenario, in which the prospect of reward optimizes preparatory processes within the short CTI, it is conceivable, to obtain larger reward-related processing improvements in the right tail, but of similar size for short and long CTI conditions. In contrast, for the case in which the reward utilization improves with increasing preparation duration, the reward-related processing improvements in the right tail might be more pronounced for the long compared to the short CTI condition, as the beneficial effect of reward prospect might increase over time, the longer participants can prepare for task execution.

13.2 Results and Discussion

For Experiment 1, the result pattern indicated a main effect of reward on RT1, participants responded faster in the reward (m = 546 ms) compared to the no reward (m = 583 ms) condition. This result indicated that participants switched their reward processing strategy between trials to improve DT performance. In addition, a main effect of CTI was obtained, with a longer RT1 in the short CTI (m = 577 ms) compared to the long CTI condition (m = 548 ms), indicating the temporal preparation effect on task 1 performance (Niemi & Näätänen, 1981).

Most importantly, for the issue of the temporal dynamics of reward utilization an overadditive interaction of reward and CTI on RT1 was obtained (see Figure 13.1) with an increased reward effect in the long CTI (m = 45 ms) compared to the short CTI (m = 30 ms) condition. This effect pattern is in line with the assumption that reward utilization improved with increasing CTI length.

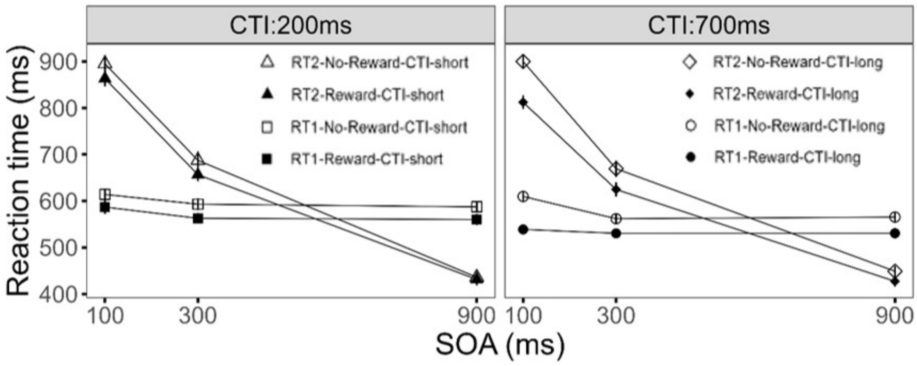

Figure 13.1: Mean reaction time of task 1 (RT1) and task 2 (RT2) as a function of reward, stimulus-onset asynchrony (SOA) and cue-target interval(CTI). Error bars represent the standard error of the mean.

As depitcted in Figure 13.2, the RT1 distribution analysis indicated, larger reward effects with an increasing CTI, as reflected by an interaction of reward and CTI. The size of the reward effect further increased as RT1 got slower, which was reflected by an interaction of reward, CTI and percentile. In sum, these results suggest, that the reward-related processing improvements increased with a longer preparatory interval, especially optimizing the cognitive processing chain during trials with longer RTs (similar effects on RT2 were obtained).

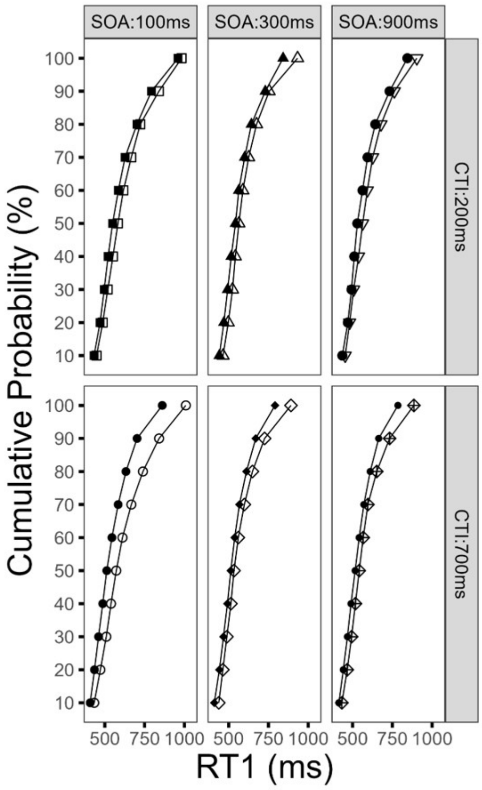

Figure 13.2: Reaction time distribution analysis of task 1 (RT1) as a function of reward, stimulus-onset asynchrony (SOA), cue-target interval (CTI) and percentile for Experiment 1. Filled symbols denote the reward condition. Open symbols denote the no reward condition.

For task 2, the reward- and preparation-related results were similar to the results obtained for task 1 performance. Most importantly, for the issue of the temporal dynamics of reward utilization, I obtained an overadditive interaction of reward and CTI on RT2, with larger reward effects in the long CTI (m = 51 ms) compared to the short CTI condition (m = 26 ms). In addition, an overadditive interaction of reward and SOA on RT2 was obtained with larger reward effects for SOA 100 (m = 62 ms) compared to SOA 900 (m = 13 ms). Such a reward effect pattern is consistent with the assumption that the prospect of reward affected the pre- and/or bottleneck stages of task 1 which propagated at short SOA from task 1 onto task 2, reducing RT 2, as well.

For Experiment 2, the analysis of task 1 and task 2 performance indicated similar reward- and preparation-related effects as in Experiment 1 (see Figure 13.3). Most importantly, for the issue of the temporal dynamics of reward utilization in DT conditions of reduced temporal expectation, an overadditive interaction of reward and CTI on RT1 and RT2 was obtained. For RT1 the reward effect in the long CTI condition (m = 69 ms) was increased compared to the short CTI condition (m = 51 ms); which was also the case for the reward effect in the long CTI condition (m = 64 ms) compared to the short CTI condition (m = 43 ms) for RT2. This effect pattern is in line with the results of Experiment 1, indicating that for DT conditions of reduced temporal expectation, the reward utilization improved with increasing preparation duration.

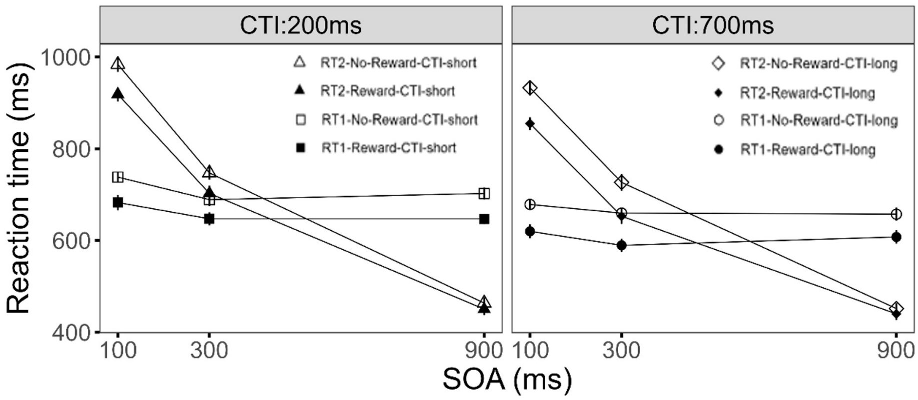

Figure 13.3: Mean reaction time of task 1 (RT1) and task 2 (RT2) as a function of reward, stimulus-onset asynchrony (SOA) and cue-target interval (CTI). Error bars represent the standard error of the mean

As illustrated in Figure 13.4, the distribution analysis of RT1 showed, increased reward effects with an increasing CTI, which was reflected by an interaction of reward and CTI. As RT1 got slower, the size of the reward effect increased, as indicated by an interaction of reward, CTI, and percentile. Taken together, for task conditions with reduced temporal expectation, the reward effects got larger with an increasing preparatory interval; and this effect was especially pronounced during trials for which RT1 was increased, suggesting that the prospect of reward could more efficiently optimized an inefficient cognitive processing chain during longer intervals (similar effects on RT2 were obtained).

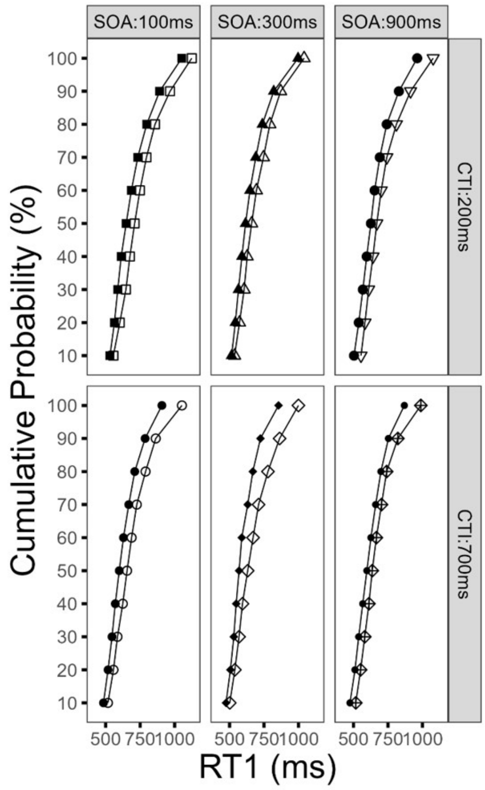

Figure 13.4: Reaction time distribution analysis of task 1 (RT1) as a function of reward, stimulus-onset asynchrony(SOA), cue-target interval (CTI) and percentile for Experiment 2. Filled symbols denote the reward condition. Open symbols denote the no reward condition.

To summarize the results, Experiment 1 and 2 provided evidence for the assumption that participants flexibly switched their reward processing strategy between trials, to improve their DT performance. This led to reward-related processing improvements on pre- and/or bottleneck stages of task 1, which were propagated via the bottleneck mechanism onto the task 2 processing chain, reducing RT2. Furthermore, for the block-wise and randomized CTI conditions, increased preparation time resulted in increased reward effects on the means and the distribution of RTs of task 1 and task 2. This effect pattern suggests that reward utilization is affected by the length of the preparatory interval. Taken together, the findings demonstrate novel evidence on the temporal dynamics of reward utilization in DT situations.

To sum up Study 3, both experiments provided evidence consistent with the assumption that participants flexibly switched their reward processing strategy, between trials, to improve their DT performance. This extends previous results in which the prospect of reward was applied block-wise. Consequently, this suggests, that a block-wise and trial-wise reward application, mainly shortened the processing stage(s) before or/at the bottleneck of task 1. In addition, the reward-related processing improvements increased with an increasing CTI, thereby suggesting that reward effects reflect an additional processing improvement, on top of the preparation-related processing improvements. I will address these points in more detail in the General Discussion section of this dissertation in Chapter 12.

14. General Discussion

For the discussion section of this dissertation, I will first summarize the findings of Studies 1-3 before a discussion of the most relevant findings. After that I will finish this chapter by indicating the limitations providing an outlook for future investigations closing the chapter with a conclusion.

14.1 Summary of the results

In Study 1, I addressed the issue of reward effect localization, in the processing chain of task 1 and task 2, for selectively rewarding task 1 performance, by employing an auditory-visual PRP DT. The results of Experiment 1 indicated that the prospect of reward affected the processing stages before or/at the bottleneck of task 1, which were transmitted via the bottleneck mechanism onto the processing chain of task 2 reducing RT2 as well. In addition, a fraction of the reward effect emerged directly on the motor stage of task 1. For Experiment 2, I added a difficulty manipulation of the response selection stage of task 2 to infer which processing stage of task 2 was processed earlier due to the reward prospect to task 1. The results of Experiment 2 demonstrated that the response selection stage of task 2 was processed earlier in the reward compared to the no reward condition, reflecting the reward-related task 2 processing improvements. In sum, the results demonstrate a consistent reward effect locus, providing novel evidence on which processing stages are improved by a reward prospect. Furthermore, the results demonstrated the task conditions, for which reward-related transmission effects on the task 2 processing time emerge.

In Study 2, I investigated how DT processing is affected, if the reward prospect is tied to the task, for which the processing chain is interrupted by a central bottleneck. The results of Experiment 1 indicated that the task-selective reward association to task 2 improved task 1 processing. This resulted in reward-related processing improvements of pre-and/or bottleneck stages of task 1, which were transmitted via the bottleneck mechanism onto the task 2 processing chain reducing RT2 as well. Furthermore, the reward-related processing improvements were increased for task 2 compared to task 1 indicating a direct reward effect on the task 2 processing chain in addition to the propagated effect. For Experiment 2, I localized the bottleneck between the tasks to infer over which processing stage the reward-related processing improvements propagated onto the processing chain of task 2. The results of Experiment 2 indicated that the reward-related processing improvements were transmitted from the response selection of task 1 onto the response selection of task 2. All in all, Study 1 and Study 2 demonstrated how the prospect of reward affects DT processing and provided conclusive evidence for which PRP DT conditions reward-related transmission effects between task 1 and task 2 emerge, thereby extending previous evidence on reward-related transmission effects between tasks.

In Study 3, as a first issue, I investigated whether participants flexibly switched their reward processing strategy between trials to improve their DT performance. To that end, I combined a trial-wise reward prospect (i.e. signaled by a cue) with an auditory-visual PRP DT. The results of Experiment 1 demonstrated, that participants switched their reward processing strategy between trials, resulting in improved RT1 and RT2 performance. The reward-related processing improvements of pre-and/or bottleneck stages of task 1, were propagated via the bottleneck mechanism onto the task 2 processing chain, reducing RT2, as well. As a second issue, I investigated, the relation of reward- and preparation-related processing improvements. To that end, I employed, block-wise CTIs, of either 200 ms or 700 ms, before task 1 presentation, in Experiment 1. This led to larger reward effects in the long compared to the short CTI condition on RT1 and RT2 performance. This finding is in line with the assumption that the utilization of reward information increases with increasing length of the CTI. For Experiment 2, the presentation of CTIs was randomized within blocks, resulting in larger reward effects in the long CTI compared to the short CTI condition on RT1 and RT2 performance. The results are consistent with the assumption that reward utilization, for task conditions of reduced temporal expectation, increased with increasing length of the CTI. In sum, the results of Study 3 demonstrate, that the prospect of reward leads to larger processing improvements with increasing preparation time, as a result, such an effect pattern could indicate that the prospect of reward elicits additional cognitive processing, beyond improved preparation.

14.2 The prospect of reward to task 1 performance

For Study 1, I investigated how a task-selective reward association to task 1 affects PRP DT processing. The results demonstrated that the prospect of reward shortened pre- and/or bottleneck stages of task 1, which led to an earlier onset of the response selection stage of task 2, in the reward compared to the no reward condition, reducing RT2. In addition, some proportion of the reward effect on task 1 was not propagated onto task 2, therefor improving motor processes of task 1. These novel results extend previous studies which reported that the prospect of reward improved processes related to the perceptual stage, the response selection stage, or the motor stage in single task studies (Asutay & Västfjäll, 2016; Bundt et al., 2016; Chiew & Braver, 2016; Engelmann, 2009; Hübner & Schlösser, 2010; Kiss et al., 2009; Krebs et al., 2011; Krebs & Woldorff, 2017).

In particular, the results of these investigations indicated that reward prospect can improve attentional and/or early perceptual processing. In a recent investigation Asutay & Västfjäll (2016) demonstrated that reward-related attentional learning leads to effects on attentional selection and perceptual acuity in an auditory detection task. The authors concluded, that the motivational value biased the auditory attentional selection of the auditory stimuli during task processing leading to the improved task performance in the reward compared to the no reward condition.

In connection to the current case, it is conceivable that the prospect of reward to the auditory task 1 led to an increased attentional effort in the reward compared to the no reward condition resulting in improved quality of auditory sensory processing. Such a conclusion would be consistent with the finding of a reduced error rate of task 1 in the reward compared to the no reward condition (see Appendix A). The improved RTs in combination with the improved accuracy in the reward in contrast to the no reward condition could reflect an improved rate of evidence accumulation. Consequently, the shortening of perceptual processes would result in an earlier onset of the subsequent processing stages, i.e. the response selection and the motor stage, which would, at shorter SOAs, lead to an earlier onset of the response selection of task 2, to reduce RT2 as well.

Furthermore, reward-related stage shortening of the response selection stage would also lead to a reward-related transmission effect via the central bottleneck mechanism from task 1 onto task 2. This reward effect pattern would be in line with evidence from several other studies that demonstrated that the reward prospect can improve such processes as updating as well as maintaining task-relevant information in working memory, in turn reducing the processing time of the response selection stage (Etzel et al., 2016; Kennerley & Wallis, 2009). Taken together, the present results indicate that the largest part of the reward effect emerged in the combined processing duration from the perception of the stimulus until the end of the response selection of task 1 resulting in reward-related processing transmissions via the central bottleneck mechanism onto the task 2 processing chain reducing RT2.

Finally, a proportion of the reward-related processing improvement from task 1 was not transmitted onto the processing chain of task 2, as the reward effect was localized at the post-bottleneck stage of task 1, after the bottleneck stage. Previous investigations provided evidence indicating that the prospect of reward can improve motor-related processing in sensory-motor RT tasks, as a result, in the current case, the prospect of reward could have directly improved task 1 motor processing, leading to a further RT1 reduction (Bundt et al., 2016). In sum, the results indicate that the prospect of reward to task 1 performance affected the pre- and/or bottleneck stages *and* the post-bottleneck stage task 1, suggesting a direct reward effect on task 1 motor processing.

Previously, there were inconclusive reports on whether the prospect of reward to one task will lead to reward-related transmission effects to the other task, as Rieger et al. (2021), reported no reward-related processing improvements on task 2 processing time, for DT situations (see also: Yildiz et al., 2013). Related to the current study, the combination of the effect propagation logic with a PRP DT approach allows for a precise assessment of reward-related transmission effects between task 1 and task 2. In detail, the evidence indicates that the reward prospect to task 1 performance led for short SOA conditions, to an earlier onset of the response selection stage of task 2, reducing RT2. In contrast, for the long SOA condition no reward-related transmission effect from task 1 to task 2 emerged. In sum, as a result of the temporal overlap of the processing chains of task 1 and task 2, the central bottleneck emerges linking both processing chains; via this linking, reward-related processing improvements of task 1 can affect task 2 processing as well.

A further issue was whether the prospect of reward to task 1 performance will lead to a more parallel processing of the response selection stages. Such a possibility had been mentioned by authors like (Meyer & Kieras, 1997; see also: Salvucci & Taatgen, 2008), suggesting that participants might engage in a more risky DT processing strategy, resulting in a more parallel processing of the response selection stages for motivated task conditions (e.g. the prospect of reward). In contrast, other authors proposed the idea of a central bottleneck due to structural reasons leading to serial processing of the response selection stages of both tasks (Pashler, 1994). The obtained results indicated a serial scheduling of the response selection stages constituting a bottleneck at the central stages of the processing chain of both tasks. Crucially, the prospect of reward did not alter this processing architecture, which could be the case under the assumption of a strategical bottleneck operating between tasks. Instead, the results favor the assumption that the central bottleneck architecture was not changed by the reward prospect to task 1 performance. In sum, while the prospect of reward improved DT performance, as reflected by the reward effects on task 1 and task 2 performance, the prospect of reward had not lead to a change in the processing of the response selection stages from serial to parallel processing; a finding that was further corroborated by the results of Study 2 (Fischer et al., 2018; Han & Marois, 2013).

14.3 The prospect of reward to the task interrupted by a bottleneck

For Study 2, I investigated how DT processing is affected by a reward prospect which is associated to task 2 for which the processing chain is interrupted by a central bottleneck. The results indicated that the task-selective reward association to task 2 affected task 1 processes before or/at the bottleneck. As a result, these reward-related processing improvements were transmitted at short SOA, via the central bottleneck mechanism, onto the response selection stage of task 2, reducing RT2. Furthermore, the reward prospect to task 2 directly affected the bottleneck and/or post-bottleneck stages of task 2, without being transmitted from task 1. These novel results indicate how the prospect of reward for a task that will be encountered in the future, can boost task performance for the immediately following task.

The results of Study 2 raise the question of why the prospect of reward to task 2 performance improved task 1 processing time. This finding could be related to the way participants represent and prepare the DT situation in their minds. By now there is accumulating evidence that participants do not represent the component tasks of the DT situation as two isolated processing chains. Instead various studies reported evidence consistent with the assumption that both component task representations are linked to a higher-order DT representation, for which participants prepare the processing sequence of task 1 and task 2 prior to task 1 onset (Hirsch et al., 2018; Kübler et al., 2018; Schubert & Strobach, 2018). Consequently, the reward prospect to task 2, improves already task 1 processing which leads to reward-related transmission effects, via the bottleneck mechanism, onto the task 2 processing chain, reducing RT2 as well. Taken together, these novel results indicate a potential mechanism for how the reward prospect to a future task will improve immediate task performance, thereby extending previous results (Rieger et al., 2021; Zedelius et al., 2012)

An alternative interpretation of the reward-related processing improvements of task 1, could emphasize that the prospect of reward to task 2 performance, improved preparation to process and execute the upcoming task (e.g. Zedelius et al., 2012). This assumption suggests a rather unspecific reward-related processing improvement, that will emerge for the task encountered next. Such an assumption could explain, the comparable error rates in the reward compared to the no reward condition (see Appendix B), by assuming only a speed-up of RTs for reward conditions. However, as elaborated on in detail below, the size of the reward effect varied as a function of reward assignment, across Study 1 and 2. Consequently, the reward effect for the rewarded task 2 was increased compared to the nonrewarded task 1, as a result, such a finding seems less compatible with the assumption of a purely unspecific reward-related processing improvement (see also: Kleinsorge & Rinkenauer, 2012; Umemoto & Holroyd, 2015). Instead, such a finding could indicate that participants process the two tasks with different and separate reward values, which leads to different outcomes of the reward effects in DT situations.

As indicated, the size of the reward effect varied as a function of reward assignment for Study 1 and 2. Consequently, the results across Study 1 and Study 2 allow for a more comprehensive assessment of how the prospect of reward to either task 1 or task 2 performance affects the size of the reward effect. In detail, the differences in the reward effect, across studies, could reflect strategic processing adjustments for the allocation of mental effort, for optimizing task performance, to obtain a reward (Kool & Botvinick, 2018). For the case of Study 1, participants were rewarded for their task 1 but not for their task 2 performance. As a result, participants, could have allocated increased mental effort to the execution of task 1, resulting in larger reward-related processing improvements on task 1 compared to task 2. In contrast, for Study 2, the prospect of reward was assigned to task 2 but not to task 1, as a result, participants might have allocated mental effort to task 1 processing, as improved task 1 processing, will lead to improved task 2 processing, via the bottleneck mechanism. The larger reward-related processing improvements for task 2, could reflect, an *additional allocation* of mental effort to the processing and execution of task 2 by the participants.

The current findings in combination with the findings from Study 1 now enable a more precise discussion of reward-related transmission effects between tasks in PRP DT situations. For the current case, especially the result of Rieger et al. (2021) deserve a comment, as the authors reported no reward-related task 2 improvements in their study. While the authors suggested that the coordination of two motor responses might have impeded reward-related task 2 improvements this interpretation seems improbable considering the results of Study 1 and 2. In particular, the results indicated that task 1 processing stages before or/at the bottleneck were shortened reducing RT1. Consequently, the reward-related processing improvements were propagated via the central bottleneck mechanism onto the task 2 processing chain reducing also RT2. In contrast, to the interpretation by Rieger et al. (2021), the *execution* of two motor responses, could reflect, a precondition for the observed reward-related transmission effect between tasks.

14.4 Investigation of the temporal dynamics of reward utilization

To discuss Study 3, both experiments provided evidence consistent with the assumption that participants flexibly switched their reward processing strategy between trials, to improve their DT performance. The results indicated that the prospect of reward rapidly improved mean RT1 and RT2 performance. In addition, these effects were further specified by the results of a distribution analysis of RTs indicating that longer RTs were especially affected by the prospect of reward. Former studies reported that increased mental effort can lead to improved attentional mobilization which resulted in the stabilization of task performance (Falkenstein et al., 2003; Kleinsorge, 2001; Steinborn et al., 2017), as indicated by an effect of mental effort on the right tail of the RT distribution. For the current case, it is conceivable, that the prospect of reward stabilized DT performance by reducing attentional fluctuation of DT processing in the reward compared to the no reward condition. Taken together, the results suggest that participants flexibly switched their reward processing strategy, leading to improved and stabilized DT performance.

The current findings provide important evidence for the ongoing discussion on whether reward-related processing improvements reflect in essence preparation-related processing improvements as suggested by several authors (Capa et al., 2013; Kleinsorge & Rinkenauer, 2012; Rieger et al., 2021; Schevernels et al., 2014; Zedelius et al., 2012). Or whether the prospect of reward results in *further* effects on task performance beyond the preparation-related performance improvements, which would make it plausible to assume that the prospect of reward elicits additional cognitive processing.

The current findings support the latter position, by providing evidence for the assumption that the prospect of reward leads to *further* processing improvements on top of the temporal preparation effect on DT performance. In particular, the obtained results indicate that for optimal preparatory DT conditions as reflected by the improved RT1 and RT2 performance in the long compared to the short CTI condition, the prospect of reward *further* improved DT performance. This is reflected by the larger reward effects in the long compared to the short CTI condition on RT1 and RT2 performance. Such an effect pattern is not be consistent with the assumption that reward-related processing improvements reflect pure preparation-related processing improvements; on the opposite the effect pattern favours the assumption that the prospect of reward elicits a further effect on DT processing which is added to the temporal preparation effect. Taken together, these results indicate novel evidence that the reward-related performance improvements go beyond a preparation-related performance improvement.

Consequently, this pattern of results raises the issue through which mechanism the larger reward-related processing improvements emerged in the long compared to the short CTI condition. One possibility could be that the prospect of reward and temporal preparation affected identical processes, leading to the observed improvements. In particular, the chronometric analysis indicates a pre-motoric locus of the reward-related processing improvements of task 1. Similarly, previous chronometric investigations on the locus of the temporal preparation effect, provided evidence consistent with the assumption, that high in contrast to low temporal preparation affects pre-motoric processes of task 1 (Bausenhart et al., 2006, 2010), a finding which is in line with the results of Study 3 (see Appendix C for details). Follow-up investigations, further pinpointed the locus of the temporal preparation effect, providing evidence consistent with the assumption, that high in contrast to low temporal preparation improves the onset of sensory information accumulation (Seibold et al., 2011). Consequently, for the current case, the locus of the reward effect as well as the temporal preparation effect were on pre-motoric processing stages of task 1. As a result, it is conceivable, that both manipulations affected the onset of sensory information accumulation, potentially leading to the overadditive effect, as reflected by the larger reward effect in the long compared to the short CTI condition on RTs.

Taken together, the provided evidence, makes it probable that improved preparation is not the main mechanism driving reward-related processing improvements. Instead, it could be worthwhile to consider, whether mental effort could play a role for the emergence of reward-related processing improvements. In particular, previous studies, reported that mental effort can lead to improved attentional mobilization which resulted in the stabilization of task performance, reflected by larger effects of mental effort on longer RTs (Falkenstein et al., 2003; Kleinsorge, 2001; Steinborn et al., 2017). For the current investigation, the reward effects increased as RTs got slower, hence demonstrating a similar effect pattern. Furthermore, the application of a mental effort and a reward prospect instruction are similar, as a result, it could be beneficial, to consider how these two concepts are related and how to empirically disentangle them in the future, to further elucidate the mechanism of reward-related processing improvements.

14.5 Limitations and outlook

In the present dissertation, I utilized chronometric methods to investigate how the prospect of reward affects DT processing, allowing me to extend previous conclusions concerning reward-cognition interactions in sensory-motor RT tasks. In particular, previous investigations often focused on the elucidation of reward-related modulations of e.g. cognitive flexibility, conflict processing, or visual attention (Fröber & Dreisbach, 2016; Jimura et al., 2010; Kiss et al., 2009; Krebs et al., 2010; Mittelstädt et al., 2024). The current results emphasize a different perspective, by applying task-selective reward associations to analyse and compare the magnitude of reward-related processing improvements, occurring between the tasks. The application of analytic tools such as the locus-of-slack and effect propagation methods (Janczyk et al., 2019; Pashler & Johnston, 1989; Schubert, 1999; Schweickert, 1980) in combination with task-selective reward associations enabled the investigation of reward-related transmission effects between tasks.

However, some open issues related to the localization of reward-related processing improvements, remained, that can be addressed in future investigations. In particular, in Study 1 and 2, I localized the reward effect in the processing chain of task 1 and task 2. The results indicated that selectively rewarding either task 1 or task 2 performance, shortened the processing stages before or/at the bottleneck of task 1, which led to reward-related transmission effects via the bottleneck mechanism, onto task 2. The current experimental setup was not suited to differentiate whether the prospect of reward improved the pre-bottleneck or bottleneck stage of task 1.

To investigate this issue, chronophysiological methods, i.e. the combination of chronometric methods and electrophysiology, with high temporal resolution, can be applied (Leuthold et al., 1996, 2004; MÜller-Gethmann et al., 2003; Sommer et al., 2001). In particular, the measurement of motor potentials emerging in the motor cortex which are considered to reflect task-related motor-preparation can be utilized to further localize the reward effect. To that end, the stimulus-locked lateralized readiness potential (sLRP) and the response-locked LRP (LRPr) are measured to bisect the RTs in an early and late phase to observe how the prospect of reward affects the onset latency of the sLRP and the LRPr, respectively. Based upon the results of Study 1 and 2, it is possible to form precise predictions about the expected onset latency of the sLRP and the LRPr of task 1 for the case of selectively rewarding either task 1 or task 2 performance. For the former case, the reward prospect should lead to an earlier onset of the sLRP *and* LRPr, reflecting reward-related processing improvements on the pre- and/or bottleneck and the post-bottleneck stages of task 1. While for the latter case, the prospect of reward should only lead to an earlier onset of the sLRP, but not of the LRPr, reflecting the reward-related processing improvements of the pre- and/or bottleneck stages of task 1.

Furthermore, to elucidate whether the prospect of reward affected the pre-bottleneck stage of task 1, an additional component can be measured, the N2pc, reflecting attentional allocation processes, prior to the onset of the sLRP (Hackley et al., 2007). Consequently, with such an experimental set-up it would be possible to more precisely pinpoint the locus of the reward effect in the processing chain of task 1, which can elucidate whether already the pre-bottleneck stage of task 1 is affected by reward. For this case, the prospect of reward, could lead to an earlier onset of the N2pc component, reflecting an effect on attentional allocation processes by the reward prospect.

An additional focus in this dissertation was to elucidate the issue of reward- and preparation-related processing improvements in DT situations. The combination of a reward prospect with the application of preparatory intervals with varying length enabled me to elucidate the issue of reward-related processing improvements. While the current findings indicate that temporal preparation is not sufficient to explain reward-related processing improvements, some open issues should be addressed in future studies.

In Study 3, I obtained larger reward effects in the long compared to the short CTI conditions. While the results indicate that further reward-related processing improvements emerged with an increasing preparatory interval, it is an open issue, whether reward effects will emerge, if participants cannot prepare for stimulus onset. In particular, participants utilized a trial-wise reward prospect either within a 200 ms or 700 ms CTI. Thus, for both CTI conditions, a cue was presented signaling a reward or no reward trial and participants could *prepare* for at least 200 ms before stimulus onset. As a result, it is an open issue whether participants can utilize the reward information, if they can *not* prepare for the onset of the stimulus, but would have to process the reward information and the stimulus properties concurrently. For such a task condition, the cue signaling a reward or no reward trial is presented simultaneously, with the stimulus. As a result, participants could not process the information signaled by the cue and then prepare for the classification of the stimulus, but instead the information signaled by the cue and the stimulus properties have to be processed in parallel. Consequently, such a task set-up can be applied to further investigate the temporal boundary conditions for the utilization of reward information and could provide further evidence on the issue of whether preparation is a *necessary* process for the emergence of reward-related processing improvements.

Finally, I only applied two CTIs of 200 ms or 700 ms, as a result, it an open issue, how the utilization of reward information is affected by very long preparatory intervals. For such a case several possibilities are conceivable, such as a linear increase of the reward effect with an increase of the preparatory interval. Such an outcome would indicate that the prospect of reward can further optimize task processing, potentially by reducing attentional fluctuations. In contrast, it is also conceivable that the utilization of reward information reaches a ceiling, for a certain length or the preparatory interval, reflecting a natural boundary of processing optimization. As a third alternative, it could also be the case, that the reward effects decrease, as temporal uncertainty increases during very long preparatory intervals (Niemi & Näätänen, 1981), which might reduce the effect of a reward prospect. This could result in an inverted U-shaped curve of the reward effect as a function of preparatory intervals; rather low reward effect for short CTIs, increased reward effects for intermediate CTIs and again decreasing reward effects for longer CTIs. Taken together, this outlined approach can be utilized to elucidate the temporal conditions of reward-related processing optimization.

14.6 Conclusion

To infer, in the present dissertation I investigated how the prospect of reward improves DT processing. For Study 1, I demonstrated that selectively rewarding task 1 leads to reward-related processing improvements of pre-motoric (and motor) stages of task 1, this effect indicates that the prospect of reward can improve the entire cognitive processing chain. The pre-motoric reward optimization of task 1 was transmitted via the central bottleneck, leading to an earlier onset of the response selection stage of task 2, reducing RT2.

For Study 2, I demonstrated that the reward prospect to task 2, for which the processing chain is interrupted by a central bottleneck, improves pre-motoric task 1 processes. As a result, the reward-related processing improvements were transmitted, via the central bottleneck mechanism, onto the response selection of task 2, reducing RT2. Together these results provide novel evidence, indicating the DT conditions, in which, reward-related processing improvements are transmitted between tasks

For Study 3, I demonstrated that participants flexibly switched their reward processing strategy, between trials, to improve and stabilize their DT performance. This finding indicates a large level of cognitive processing potential, for task conditions with multiple tasks. Furthermore, I could show that the utilization of reward information increases with increasing preparatory interval, suggesting that the reward-related optimization processes develop over time, with a potential further increase. This finding indicates that preparation is not sufficient to explain reward-related processing improvements, as a result, further research is required to specify how the prospect of reward improves task processing. The obtained results provide relevant theoretical implications for future research on reward processing in multitasking situations. Future studies should further specify the mechanisms of reward-related processing transmissions between tasks and reward-related processing improvements, by integrating additional factors and methodologies, and by applying different multitasking paradigms.

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RESEARCH

On the localization of reward effects in overlapping dual tasks

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Abstract
In dual-task (DT) situations, performance deteriorates compared with single-task situations. Such performance decrements are frequently explained with the serial scheduling of the response selection stages constituting a bottleneck. Proof of this assumption stems from the observation that response times for the second task (task 2; RT 2) increase with decreasing stimulus-onset asynchrony (SOA).

In this study, we investigated how the reward prospect for task 1 performance affects task 1 and task 2 processing. For that purpose, we relied on the psychological refractory period paradigm (PRP) as a chronometric tool, to determine the locus of the reward effect in the processing chain of both tasks.

We obtained improved task 1 and task 2 performance; as indicated by reduced RTs in the reward compared to the no reward condition of task 1 and task 2. Furthermore, the reward effect propagated at short SOA from task 1 onto task 2, suggesting that the locus of the reward effect can be pinpointed before or at the bottleneck of task 1. Importantly, the mean reward effect on task 1 was increased compared to task 2, thus indicating that parts of the reward effect were not propagated onto task 2, therefore affecting task 1 motor processes.

In Experiment 2, we tested for the locus of the effect propagation to task 2. Therefore, we implemented a difficulty manipulation of the response selection of task 2. The results indicate that the reward effect is propagated from task 1 onto the response selection stage of task 2.

Introduction

Humans often execute two tasks at the same time or in close succession. In such dual-task (DT) situations, participants' performance often deteriorates compared to when the same tasks are performed separately. The underlying cognitive architecture has long been investigated using DT paradigms such as the psychological refractory period (PRP) paradigm. In such PRP situations participants perform two temporally overlapping choice reaction time (RT) tasks, which are separated by a variable interval between them, the stimulus onset asynchrony (SOA). The situation usually results in decreased performance compared to single-task situations referred to as dual-task costs and to a performance pattern in which the response times on the second task (task 2) are increased the shorter the SOA between the tasks. The central bottleneck model explains these costs with the serial processing of the central response selection stages, while peripheral stages (i.e. perceptual and motor stages) are assumed to be processed in parallel. It is assumed that at short SOA the response selection and motor stage of task 2 wait until the response selection of the first task (task 1) has finished. This leads to an interruption of task 2 and explains why the reaction time to task 2 (RT2) is increased at short SOA and decreases the longer the SOA between tasks. The reaction time to task 1 (RT1) is assumed to be unaffected by the SOA variation.

Despite the general debate about the nature of the bottleneck being strategical or structural (Kieras & Meyer, 1997; Pashler, 1994), numerous factors and interventions have been identified that can modulate bottleneck processing, such as e.g. training (Ruthruff et al., 2006; Schubert & Strobach, 2018; Strobach et al., 2014), age (Hein & Schubert, 2004; Strobach et al., 2012), and different input and output modality combinations (Hazeltine et al., 2006; Stelzel et al., 2006). A further relevant question in this vein

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of research is whether and how reward prospect affects DT processing (Fischer et al., 2018; Han & Marois, 2013; Yildiz et al., 2013).

Previous work of our group investigated the location of reward effects in a PRP DT scenario, in which reward was selectively provided for task 2 performance, which according to DT theories represents the task that is interrupted due to bottleneck processing in task 1 (Langsdorf et al., 2022). In that study, participants perceived an instruction that they could earn a maximum potential reward of 72 Euro Cent per block if they performed fast and accurately on task 2 while maintaining a low error rate on task 1 performance. Interestingly, we observed performance benefits in the reward compared to the no reward condition already on task 1 processing, which indicates that participants' reward prospects on task 2 improved the execution of the earlier to be processed non-rewarded task 1 and, only then, following improved the execution of task 2 (but see: Rieger et al., 2021).

Such an effect localization of reward-related task improvements to the processing stream of task 1 although the subsequent task 2 was rewarded has important implications. It indicates that the prospect of reward in PRP DT situations will not only affect the task associated with reward but that the reward-related task improvements can spillover to the non-rewarded task as well. The localization of potential reward effects in the processing chain of a DT situation can, thus, provide a clue for understanding the mechanisms of reward processing in DT situations; it can also contribute to the understanding of results from other studies investigating reward-related improvements in situations with multiple tasks and reporting inconclusive result patterns for rewarded and non-rewarded tasks.

For the current case, the results of Rieger et al. (2021) are particularly relevant. The authors reported that rewarding either mainly task 1 or task 2 performance (but with different size) in a PRP-like paradigm did not lead to reward effects on task 2 performance. In their analyses of the PRP task performance, the authors focused especially on those task conditions, in which participants had *not* responded to task 1 (no-go trials), but only to task 2 and did not find significant reward-related changes in the processing time of task 2. Considering previous findings of Langsdorf et al. (2022), it is conceivable that not responding to task 1 in the Rieger et al. (2021) study has impeded the emergence of reward effects on task 2 performance. This would be an explanation for the lacking reward effect on task 2 performance by Rieger et al. (2021), which is also at odd with the findings of other authors like Kleinsorge and Rinkenauer (2012). These authors reported the occurrence of reward effects in a non-rewarded task with a cued task switching situation in which a sudden short-termed presentation of a reward cue could have caused the allocation of processing resources to the non-rewarded task although reward boni were associated with the other task. Consequently, more research is required to foster evidence about the potential spillover of reward effects on non-rewarded tasks in multiple task situations and elucidate the mechanisms for their occurrence. In the current study, we aimed, therefore, to assess the localization of reward effects in a PRP DT scenario in more detail and focused especially on a situation in which reward was directly awarded to task 1 but not to task 2. This allowed us to assess the generalizability of our former findings of reward-effect localization in task 1 in a PRP DT situation by comparing the current findings with those of our former study (Langsdorf et al., 2022). This way we aimed to better understand the locus of reward effects in DT scenarios and, through this, to understand better the origin of potential spillover of reward effects between tasks in multiple task situations.

To outline the logic of the current study, we first discuss the previously obtained reward effects and explain the logic of the rationale, which led to the conclusion that the task 2 reward prospect affected task 1 processing and then spilled-over to the task 2 processing time (Langsdorf et al., 2022). That particular conclusion is based on *the effect propagation logic*, which predicts that a change in the processing time of pre-bottleneck and bottleneck processing in task 1 of a PRP situation will be propagated via the bottleneck mechanism onto task 2 RTs (Janczyk et al., 2019; Pashler & Johnston, 1989; Van Selst et al., 1999; Van Selst & Jolicoeur, 1997). Importantly, the response time effect on RT2 should be larger at short SOA than at long SOA because of the lacking bottleneck at the latter SOA; please, note that the lack of a bottleneck would prevent that the change of task 1 pre-bottleneck/bottleneck processing time propagates into task 2 time. In the former study, we obtained a main effect of reward on RT1 reflecting participants' faster responses in the reward compared to no reward condition. In addition, we obtained shorter RT2 in the reward compared to the non-reward condition with larger reward effects onto RT2 at short compared to long SOA. Thus, these results of Langsdorf et al. (2022) are consistent with the assumption that participants' prospect of reward on task 2 processing shortened the processing stages before or/at the bottleneck processing already in task 1 and that this effect propagated onto task 2 processing.

However, we obtained several additional findings (Experiment 1), which might suggest that the reward prospect on task 2 had not only affected task 1 pre-bottleneck and/or bottleneck processes in task 1 but also other processes; this, however, might suggest, that some portions of the reward prospect can bypass the bottleneck between tasks and affected task 2 processes *in addition* to the effects resulting from the propagation mechanism described before. For example, the obtained data pattern showed that the mean RT2 reward effect was significantly increased ($m = 47$ ms) compared to the size of the RT1 reward effect ($m = 33$ ms), which might indicate that there was an additional locus of the reward prospect directly on task 2 in addition to the reward locus on task 1 processing. Such a possibility is also supported by the observation that the task 2 reward effect at short SOA was significantly increased compared to the corresponding task 1 reward effect at short SOA (51 ms versus 28 ms). According to the effect propagation logic, the size of the reward effects on task 1 should be of the same magnitude, if the effects have propagated from task 1 to task 2 processing via the bottleneck. Therefore, the above-mentioned reward effect sizes are at odds with that prediction, and the larger reward effects at task 2 compared to that at task 1 indicate that (at least) part of the processing time reduction cannot be explained by a pure propagation account.

In addition, we obtained a significant RT2 reward effect at long SOA. Although numerically small ($m = 21$ ms) this effect cannot be explained by effect propagation from the reward-related task 1 processing time reduction because at long SOA there is no bottleneck interrupting the two tasks. Altogether, these findings could indeed indicate that at least part of the reward effects on task 2 did not result from an *in*direct effect propagation via the bottleneck but from a direct reward effect onto the task 2 processing chain, which, thus, has bypassed the bottleneck or affected directly the processing time in task 2. This would be indicative of a more complex pattern of reward prospects in overlapping DT tasks than an effect localization only on task 1 pre-bottleneck and bottleneck processes, which then spills over to the other processes of task 2.

Therefore, in the current study, we wanted to elucidate the location of potential reward effects in DT situations in more detail, by investigating the effects of a reward application on task 1 (instead of task 2); this allows us to assess the generalizability of reward effects resulting from a direct reward prospect to task 1 as compared to indirect reward effects resulting from the reward-assignment to task 2 as in our former study.

Additionally, we aimed to test which specific processes are affected in task 1 by the reward prospect during DT processing. In particular, we were interested in whether reward affects pre-bottleneck/bottleneck processing stages only, or whether post-bottleneck stages of task 1 can also be affected by reward. According to the effect propagation logic, propagation of reward effects on task 2 processing time can take place only in the first case thus causing spill over of reward effects but not in the second case.

Earlier findings on reward effects in single-task studies have provided evidence that reward can affect each of the processing stages along the processing chain in sensory-motor choice RT tasks, i.e. the perception, the response selection, or the motor stage of task 1. For example, in a study by Engelmann and Pessoa (2007), participants performed an exogenous spatial cueing task, in which participants reported the location of a peripherally cued target stimulus superimposed on either a face or a house stimulus. Before each trial a cue indicated the obtainable reward value. The results indicated a linear increase in detection sensitivity (d prime) as a function of incentive magnitude (Chiew & Braver, 2016; Engelmann, 2009; Engelmann & Pessoa, 2007; Kiss et al., 2009). Such findings are also underpinned by electrophysiological evidence, e.g., studies with event-related brain potentials with a high temporal resolution, which indicated increased early visual potentials for high-reward compared to low-reward targets (Nadig et al., 2019). While such effects would indicate that the application of reward affects early attentional and/or perceptual processes, other studies indicated that reward affects the response selection process. In particular, Chiew and Braver (2016) used an Erikson flanker task, in which cues indicated whether or not reward was obtainable, and if the upcoming task situation was congruent or incongruent. This resulted in an overadditive interaction of reward and task information improving task performance. Similar results were reported by other studies, suggesting a link between reward and effects on response selection (Etzel et al., 2016; Kennerley & Wallis, 2009).

Next to that, it is also conceivable, that the prospect of reward would affect motor processes during DT processing. In a study by Bundt et al. (2016), participants performed a horizontal Simon-task, in which a cue indicated whether a reward was obtainable or not. The authors showed that reward expectation led to enhanced motor preparation as indicated by reduced motor evoked potentials after cue presentation in cortical regions stimulated by transcranial magnetic impulses compared to no reward expectation. These and other findings indicate a close relation between motivation state and motor processing during task processing (Chiu et al., 2014; Hollerman et al., 1998; Schultz, 2000). Thus, it is conceivable that the application of reward affects motor processes instead or in addition to the perceptual and response selection processing in sensory-motor tasks.

In the present study, we applied the effect propagation logic in combination with a direct reward prospect on task 1 performance to assess (a) the reward effect on the DT performance on task 1 and task 2, and (b) to localize in more detail the specific processing stages of task 1, which are affected by a direct reward prospect on task 1. As can be seen in Fig. 1 different hypotheses can be distinguished in such an investigation.

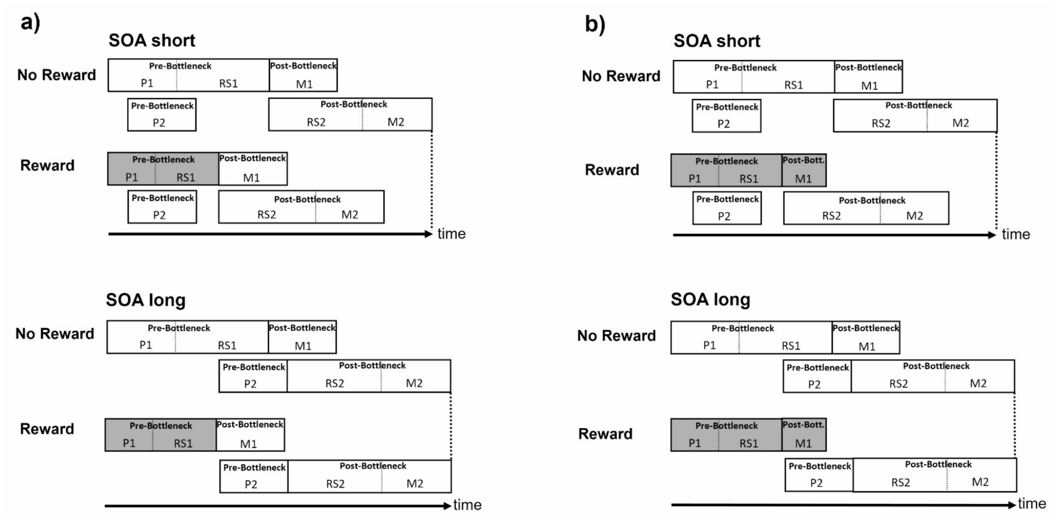

Fig. 1 Reward improves processing of task 1. Panel (**a**) depicts the case when reward reduces the processing time of the pre-bottleneck and/ or bottleneck stages of task 1. The gray shaded areas of task 1 indicate that reward shortens the pre-bottleneck and/or bottleneck stages of task 1. This results in a reward effect on RT1 and an overadditive interaction of reward and SOA on RT2. Panel (**b**) depicts the case when reward reduces the processing time of the pre-bottleneck and/or bottleneck *and* the post-bottleneck stages of task 1. The gray shaded areas of task 1 indicate that reward shortens the pre-bottleneck and/or bottleneck stages and the post-bottleneck stages of task 1. This results in an overadditive interaction of reward and SOA on RT2. And increased reward effects on RT1 compared to RT2. Pre-Bottleneck stage of task 1 comprises: P1 = perception stage of task 1; Bottleneck stage of task 1 comprises: RS1 = response selection of task 1. Post-Bottleneck stage of task 1 comprises M1 = Motor stage of task 1; Pre-Bottleneck stage of task 2 comprises: P2 = perception stage of task 2; Bottleneck stage of task 2 comprises: RS2 = response selection stage of task 2; Post-Bottleneck stage of task 2 comprises: M2 = motor stage of task 2

For example, according to the findings of our former study (Langsdorf et al., 2022), it is conceivable that a direct reward prospect for task 1 shortens the processing time of the pre-and/or bottleneck processing stages of task 1. The locus of these potential reward effects would correspond to the outlined effects of reward on the perception and/or the response selection processes. Importantly, if that was the case, we would expect effect propagation of the reward effect at short SOA onto task 2, resulting in a reward effect at short but not at long SOA. This should be reflected by an overadditive interaction of SOA and reward on RT2 as can be seen in Fig. 1a. Importantly, the size of the reward effects on task 1 and task 2 should be identical if the reward prospect exclusively leads to a shortening of the processing duration of the pre-bottleneck and bottleneck processing time in task (1) In that case, each ms of processing time reduction in task 1 should be propagated onto the processing time in task (2) According to Pashler and O'Brien (1993), such a prediction would also be consistent with the finding of an increased interdependency of RT2 on RT1 at short SOA. In contrast, the RT2 interdependency on RT1 should decrease with increasing SOA as no bottleneck emerges between both tasks. Therefore an analysis of the relationship between RT1 and RT2 can provide additional evidence for the effect propagation between tasks (for details see the results section).

However, as an alternative a direct reward prospect on task 1 could lead to an effect localization on post-bottleneck stages in task 1, i.e. the motor stages of task 1. Indeed such an effect pattern would be discrepant with the earlier findings of Langsdorf et al. (2022), in which task 2 was rewarded and the reward effect on task 1 resulted rather from an indirect reward effect on task 1. However, the fact that in the current experiment, the reward prospect is directly allocated to task 1 can cause a more efficient reward localization onto task processing including the post-bottleneck stages in task (1) In the case of a reward effect location at the post-bottleneck stages of task 1, we would expect that the amount of the reward effect on task 1 is not the same as the one on task (2) As an extreme situation, consider the case that the whole reward effect on task 1 is allocated to the post-bottleneck stage of task 1. If that was the case, then no reward-related reduction of task 1 processing time would be propagated onto task 2 processing via the bottleneck because the reward effect emerges after the bottleneck. As a result, we would expect only a reduction of RT1 in the reward compared to the no reward condition but no reward effect on RT2.

Important to note that a further situation is conceivable, in which reward shortens pre-bottleneck/bottleneck *and*, *in addition*, the post-bottleneck stages of task (1) As can be seen in Fig. 1b, this particular situation would be characterized by a combination of both effect patterns: namely by larger reward effects at short compared to long SOA on RT2 resulting from effect propagation of the reward-related reduction in task 1 chain to task 2 and, *in addition*, by larger reward effects on task 1 compared to task (2) The latter (i.e. larger task 1 than task 2 effects) would emerge if the task 1-related reward effect would not completely be propagated into the task 2 RT because part of the reward-related shortening of the task 1 processing time would be located at post-bottleneck stages; that part of the processing time reduction would not be carried over to task 2 via the bottleneck as can be seen in Fig. 1b.

In addition to the location of reward effects in task 1, we also investigated which specific processing stages of task 2 are processed earlier as a result of the reward allocation onto task 1. This question is open because different bottleneck accounts (i.e., Meyer & Kieras, 1997; Pashler, 1994) would predict that the task 2 processing chain is interrupted at different processing stages and therefore, a potential effect propagation from task 1 onto task 2 would operate via different target processes in the task 2 processing chain. In more detail, according to accounts assuming a central bottleneck (Pashler, 1994), the effect propagation from task 1 to task 2 should cause an earlier start of the response selection stage in task 2, while accounts assuming a peripheral bottleneck (Meyer & Kieras, 1997) would assume that the effect propagation should cause an earlier start of the motor stage in task 2, while the start of the response selection processes in task 2 would not be affected. We will come back to this issue and the related hypotheses when introducing Experiment 2.

Experiment 1

In Experiment 1, we tested to which degree the selective application of a reward prospect to task 1 affects participants' task 1 and/or task 2 performance. Furthermore, we investigated which processing stages of task 1 are affected by a direct reward application to task 1 performance.

To this end, we administered an auditory-visual DT with three SOAs and instructed participants that they could earn a monetary reward if their response to task 1 was fast and accurate while maintaining low error rates in task 2. Note that participants received their performance-contingent reward at the end of the experiment; therefore, it is the expectation of a potential reward and not the actual reception in a given trial that would affect participants' performance. For the sake of brevity, we will refer to this expectancy of a reward simply as the reward effect.

According to the assumption that the reward prospect for task 1 would exclusively affect the pre-and/or bottleneck processing stages of task 1, we should expect a reduction of RT1 and an effect propagation onto RT2. In detail, the effect propagation would result in a reward-related reduction of RT2 at a short SOA, which would be of the same size as that on task1, and no reward-related reduction of RT2 at a large SOA, where no task 2 interruption is taking place.

A reward effect on task 1 post-bottleneck processing, i.e. the motor stage of task 1 should lead to a reduction of the RT1, which would not propagate onto RT2. This in turn would be reflected by a larger size of the reward-related reduction of RT1 compared to RT2.

Worthwhile to note that reward can affect both, namely pre-and/or bottleneck processing stages and post-bottleneck stages of task (1) In that case, we would expect an overadditive reward X SOA interaction on RT2 suggesting reward effect propagation from task 1 to task 2; in addition (but opposite to the case of an exclusive task 1 pre-bottleneck effect), we should find larger reward effects onto RT1 compared to the reward effects on RT2 even at short SOA, where effect propagation takes place but not all of the reward effect in task 1 can be transmitted to task (2) This is so because part of the reward effect in task 1 would emerge after the bottleneck and would not be transmitted to task 2.

Materials and methods

Participants

Twenty-four healthy participants (19 *female*; *mean* (m) age = 24.35 years) were invited to take part in the experiment after obtaining written informed consent and were debriefed after the session. We chose this particular sample size based on a priori power analyses obtained with the G*Power program (Faul et al., 2007). We conducted a power analysis for the interaction effect of reward (no reward and reward) and SOA (100 ms, 300 ms, or 900 ms) on RT2. Conceptualizing, the interaction as the main effect of SOA on the differences between no reward and reward conditions. For G*Power we defined the parameters as follows: Test family: F test; statistical test: ANOVA: Repeated measures, within factors; Type of power analysis: a priori; Effect size *f*: 0.67 (which corresponds to an effect size of $\eta_p^2 = 0.31$, based on Langsdorf et al., 2022); α error prop: 0.001; Power (1-β error prob): 0.99; Numbers of groups 3; Number of measurements: 2; Corr. Among rep measure: 0.5; Nonsphericity correction ε: 1. The calculated sample size amounts to $N = 24$ for Experiment 1[1].

[1] Please, note that we calculated a similar power analysis for Experiment 2; however, with four SOA levels. This led also to an estimated

The experimental protocol conformed to the declaration of Helsinki. All participants were right-handed, German native speakers, and had normal or corrected to normal vision. Furthermore, Participants could choose between 4 Euro or course credit as a general payment, which was added by the performance-dependent amount of monetary reward (see below).

Apparatus and stimuli

Participants performed a PRP dual task consisting of an auditory and a visual choice RT task. Stimuli for the auditory task comprised of three sine-wave tones with a frequency of 250, 500, or 1000 Hz presented for 200 ms via headphones. Participants responded to the low-, middle-, and high-pitched tones by pressing the 'Y', 'X', and 'C' keys of a QWERTZ keyboard with the ring, middle, and index fingers of their left hand, respectively. For the visual task, one of three digits (*1*, *5*, or *9*) was presented centrally on a computer screen with a visual angle of 52° x 0.31° at a viewing distance of 80 cm. Visual stimuli appeared for 200 ms and participants responded to the digits in ascending order by pressing the keys 'M', ',', and '.' of a QWERTZ keyboard with the index, middle, and ring finger of their right hand. Participants were instructed to first respond to the auditory and then to the visual task. Every trial started with the presentation of a fixation cross at the center of the screen for 1000 ms followed by a blank interval for 500 ms. Subsequently, the auditory stimulus was presented for 200 ms, followed by the visual stimulus for 200 ms, separated by an SOA of either 100 ms, 300 ms, or 900 ms. After a response to both target stimuli or a maximal response duration of 3000 ms, an intertrial interval of 500 ms followed before the start of the next trial. Participants received the feedback "Falsch" (german for wrong) for 500 ms if either one or two of their responses were erroneous. If their response to either target exceeded the maximal response duration, the feedback "Zu langsam" (german for too slow) was presented for 500 ms.

Design and procedure

We applied a two-factor within-subjects design with reward and SOA as independent variables. Each block consisted of 27 trials resulting from the combination of 3 SOAs (100 ms, 300 ms, 900 ms), 3 auditory stimuli (250 Hz, 500 Hz, 1000 Hz), and 3 visual stimuli (1, 5, 9). In total 12 DT blocks were presented, and the blocked application of reward resulted in 6 reward and 6 no reward blocks. In sum, this resulted in 324 experimental trials. The procedure was as follows: The experiment started with a single-task practice phase in which participants performed 12 single-task trials for each component task (auditory and visual). The timing of these single-task trials was similar to DT trials with the exception that only one target stimulus was presented and only one response was required. These single-task trials were followed by two blocks of 27 trials of DT practice. At the start of the DT practice, Participants were instructed to respond to task 1 as soon as it was presented (Ulrich & Miller, 2008). Subsequently, the experimenter verbally instructed the participants using a standardized instruction that their task 1 performance was rewarded. And that they could earn 72 Euro Cent per block if their response to task 1 was fast and accurate, while their task 2 performance was not rewarded (however to mind low error rates for task 2). The information on whether or not a reward was obtainable was again presented before each block. In particular, to obtain a monetary reward of 72 Euro Cent per block, the RT1 as well as the error rates for task 1 have to be fast and accurate while considering low error rates for task 2. Participants' thresholds for earning a reward were calculated based on their mean RT1 performance and their mean error rates in reward blocks, both indices in a given reward block were compared to these thresholds, to decide whether or not participants receive a reward. For the first reward block, we set a pre-defined deadline of 850 ms for task 1 performance as well as 89% accuracy, based on previous studies (Langsdorf et al., 2022; and pilot studies). If either participants' mean RT1 or their mean error rates met the pre-defined threshold, they would receive 72 Euro Cent. If none of their performance measures were below the criterion measures, they received no reward. Thereafter, the reference RT1 was updated by averaging the pre-defined deadline (850 ms) and the mean RT1 of the previous reward block. Similarly, the mean error rate was updated. After each block, participants received feedback about their mean RT1 and percentage of correct trials, and for reward blocks, whether they earned a reward (and how much reward they had earned so far). The order of the 6 reward and 6 no reward blocks was randomized. Importantly, participants were naïve about the threshold computations for obtaining a reward.

Statistical Analysis Mean RTs and error rates were analyzed separately for RT1 and RT2 using an ANOVA with the within-subjects factors reward and SOA. A significance threshold of 5% was used for all analyses. The *p* values of the ANOVAs were adjusted according to the Greenhouse-Geisser correction when necessary. For the RT analyses, trials with at least one erroneous response ($m = 7\%$) and outliers that deviated more than +/- 2.5 SD for each participant and factor combination ($m = 2\%$) were excluded from the data set. Furthermore, trials were excluded that met the criterion of response grouping (RT2 – RT1 + SOA) < 200

sample size of $N = 24$.

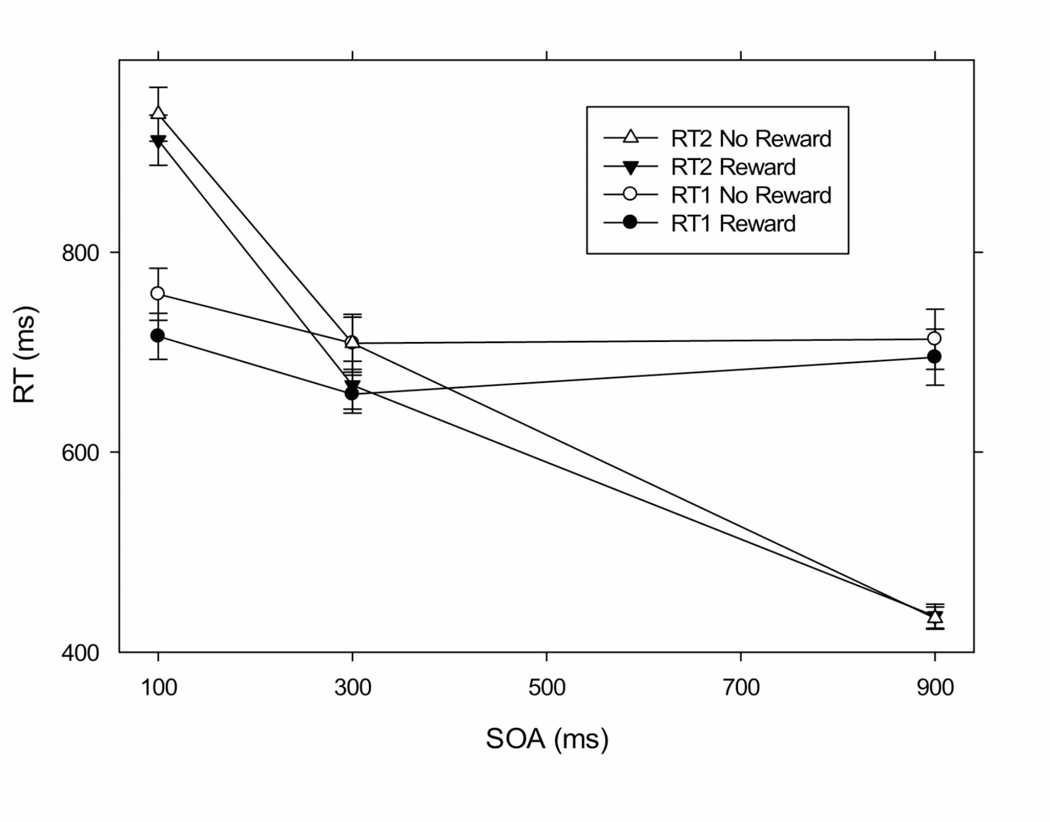

Fig. 2 Mean RT1 and RT2 as a function of SOA and reward for Experiment 1. Error bars represent the standard error of the mean

Table 1 Mean rates of errors for task 1 and task 2 in % (and standard deviation) from experiment 1 as a function of reward and SOA

	Experiment 1			
	Error rates			
	reward		no reward	
SOA	Task 1	Task 2	Task 1	Task 2
100	9.98% (6.06%)	6.12% (5.87%)	16.18% (15.75%)	10.63% (7.80%)
300	5.80% (5.78%)	5.15% (6.19%)	8.86% (8.11%)	5.31% (7.80%)
900	4.19% (4.07%)	4.99% (4.27%)	6.28% (5.85%)	8.70% (6.94%)

(Miller & Ulrich, 2008). The data set of one participant had to be excluded due to technical issues, resulting in 23 data sets for further analysis.

Results

Task 1

We first tested for the effects of reward on task 1 performance. We obtained a significant main effect of the factor reward, $F(1, 22) = 24.762$, $p < .001$, $\eta_p^2 = 0.530$. Participants' RT1 was reduced in the reward ($m = 690$ ms) compared to the no reward ($m = 726$ ms; see Fig. 2) condition. Furthermore, we obtained a significant main effect of the factor SOA, $F(1.236, 46) = 5.203$, $p < .024$, $\eta_p^2 = 0.191$, on RT1. Such effects of SOA on task 1 are often explained by participants' tendency for response grouping (Strobach et al., 2015a; Ulrich & Miller, 2008). The interaction of the factors Reward × SOA was marginally significant, $F(2, 44) = 3.079$, $p = .056$, $\eta_p^2 = 0.123$. Further tests revealed a trend toward a larger reward effect at SOA 100 ($m = 41$ ms) compared to SOA 900 ($m = 19$ ms), t(22) = 1.541, p =. 066; and a larger reward effect at SOA 300 ($m = 51$) compared to SOA 900, t(22) = 2.526, $p = .009$. While the reward effects at SOA 100 and SOA 300 were not different, t(22) = − 0.779, $p = .222$.

Mean RT1/RT2 as a function of reward and SOA For the error rates in task 1, we observed a significant main effect of the factor reward, $F(1, 22) = 10.666$, $p < .004$, $\eta_p^2 = 0.327$. The error rates were lower in the reward ($m = 7\%$) compared to the no reward ($m = 11\%$) condition. Furthermore, we observed a significant main effect of the factor SOA, $F(1, 22) = 18.216$, $p < .001$, $\eta_p^2 = 0.453$. The error rates were higher for SOA 100 ($m = 13\%$) compared to SOA 300 ($m = 7\%$) and SOA 900 ($m = 5\%$). The interaction of the factors Reward × SOA, $F(1.713, 44) = 1.713$, $p = .201$, $\eta_p^2 = 0.072$ did not reach significane.

Task 2

We observed a significant main effect of the factor reward, $F(1, 22) = 12.876$, $p < .002$, $\eta_p^2 = 0.369$ on RT2. Participants responded faster in the reward ($m = 672$ ms) compared to the no reward ($m = 692$ ms; see Fig. 2) condition. Furthermore, we found a significant main effect of the factor SOA, $F(1.364, 44) = 442.265$, $p < .001$, $\eta_p^2 = 0.953$. RT2 increased from SOA 900 ($m = 435$ ms) to SOA 100 ($m = 925$ ms), indicating the typical PRP effect (Pashler, 1994; Schubert, 1999).

Importantly, we observed a significant overadditive interaction of the factors reward and SOA, $F(2, 44) = 5.496$, $p < .007$, $\eta_p^2 = 0.200$ on RT2. Pairwise comparisons showed a significantly larger reward effect at SOA 100 ($m = 27$ ms) compared with SOA 900 (m = -2 ms), $t(22) = 2.429$, $p < .024$. While the reward effect at SOA 100 ($m = 27$ ms) was not different compared to the reward effect at SOA 300 ($m = 38$ ms), t(22)=-0.924, $p = .183$. This overadditive interaction of reward and SOA on RT2 indicates that the reward effect propagates from task 1 onto task 2. This is in line with previous evidence (Langsdorf et al., 2022), as well as with the assumptions described in the introduction part, and demonstrates that the reward application to task 1 affects the pre-and/or bottleneck processing stages of task 1. Further analysis will focus on potential additional effects of reward on other task 1 processing stages (see below).

For the error rates in task 2, the factor reward reached significance, $F(1, 22) = 9.49$, $p < .005$, $\eta_p^2 = 0.301$. The error rates in the reward ($m = 5\%$) compared to the no reward ($m = 8\%$) condition were reduced. The effect of the factor SOA reached significance, $F(1, 22) = 3.609$, $p < .035$, $\eta_p^2 = 0.141$. This indicated increased errors during SOA 100 ($m = 8\%$) compared to SOA 300 ($m = 5\%$), but not compared to SOA 900 ($m = 7\%$). The interaction of the factors Reward × SOA, $F(2, 44) = 1.879$, $p = .165$, $\eta_p^2 = 0.079$, did not reach significance.

Relationship between RT1 and RT2

The subsequent analysis focused on the relationship between RT1 and RT2 in order to investigate in more detail the effect propagation between task 1 and task 2. The assumption that effect propagation had taken part from task 1 to task 2 processing time predicts a robust interdependency of RT2 on RT1 at shorter SOAs as a slower response to task 1 should lead to a slower response to task 2 due to the bottleneck mechanism. In contrast, at longer SOAs this interdependency should decrease as with reduced temporal overlap no bottleneck emerges between the tasks. To investigate the relationship between the speed of both responses we relied on the approach of Pashler and O'Brien (1993). For that purpose, RT1 was rank-ordered and split into quintiles for each factor combination. Subsequently, the mean RT2 of the corresponding factor combination was computed. For all points mapped on the plot, the value on the y-axis denotes the mean RT2 for those trials for which the RT1 lies within a particular quintile, while the value on the x-axis identifies the mean RT1 for this particular quintile.

Figure 3a shows that an increase in RT1 led to a rise in RT2 as well. Most importantly, as SOA was reduced from 900 ms to 100 ms, the dependency of RT2 on RT1 increased. This observation was verified by the results of an ANOVA with RT2 as the dependent variable and the factors reward, SOA, and RT1 broken into quintiles; here, we obtained a significant interaction of the factors SOA and quintile, $F(8, 176) = 67.61$, $p < .001$, $\eta^2 = 0.137$.

Moreover, as depicted in Fig. 3a we obtained a significant interaction of the factors reward and SOA, $F(2, 44) = 3.43$, $p < .041$, $\eta^2 = 0.004$, suggesting larger reward effects at shorter compared to longer SOAs on RT2. This result replicated the finding obtained from our previous analysis of task 2 performance.

In addition, we found several other effects. Figure 3a displays that the reward effect was increased for larger RTs compared to smaller RTs, which is reflected by a significant interaction of the factors, reward, and quintile, $F(4, 88) = 7.96$, $p < .001$, $\eta^2 = 0.006$; this is consistent with a proposal of Hübner and Schlösser (2010) that the prospect of reward can reduce lapses of attention of participants, which are usually among the longer RTs.

We also obtained a significant main effect of the factor SOA, $F(2, 44) = 381.85$, $p < .001$, $\eta^2 = 0.708$ and a main effect of the factor quintile, $F(4, 88) = 131.62$, $p < .001$,

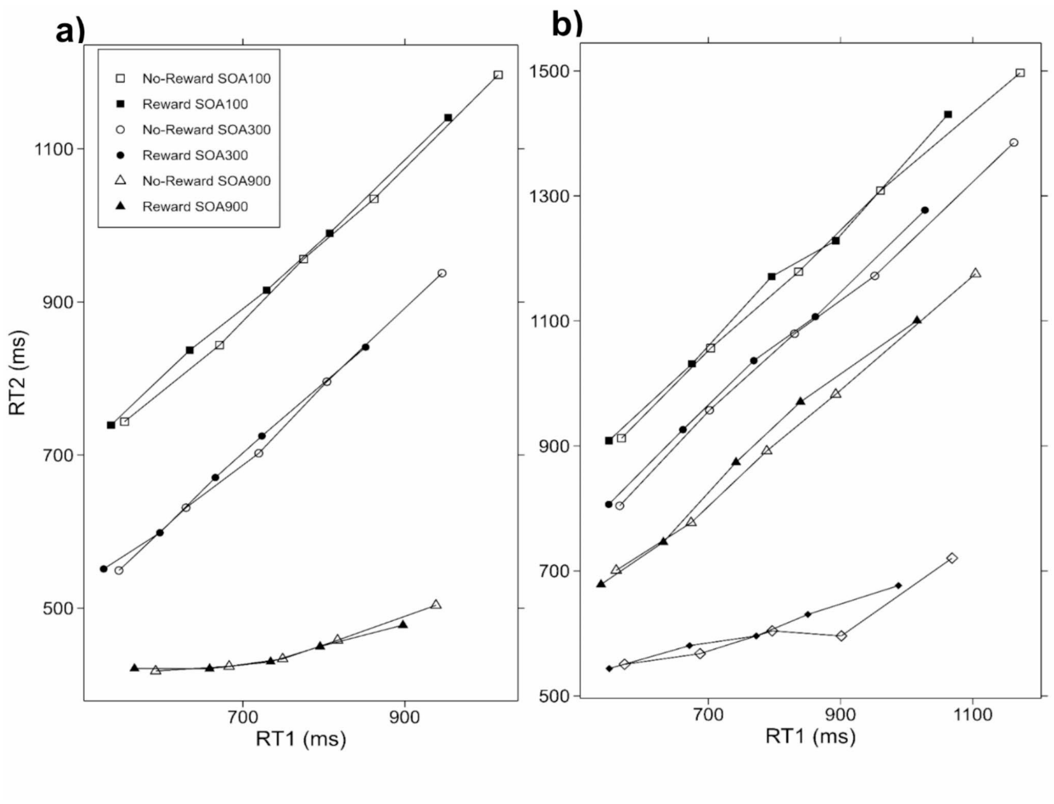

Fig. 3 Mean RT2 as a function of reward, SOA, and RT1 (broken into quintiles). Panel **a**) represents the data from Experiment (1) Panel **b**) represents the data from Experiment (2) The legend for panel b: squares denote SOA 50, circles denote SOA 150, triangles denote SOA 300, and diamonds denote SOA 900. Filled symbols represent the reward condition and empty symbols represent the no reward condition

Table 2 Mean reward effects for task 1 and task 2 in ms (and standard deviation) from experiment 1 as a function of SOA

	Experiment 1	
	Reward effects	
	Task 1	Task 2
SOA		
100	41 ms (11 ms)	27 ms (10 ms)
300	51 ms (11 ms)	38 ms (11 ms)
900	18 ms (10 ms)	-2 ms (6 ms)

$\eta^2 = 0.355$. The factor reward reached significance, $F(1, 22) = 12.94$, $p < .002$, $\eta^2 = 0.011$, indicating shorter RTs in the reward compared to the non-reward condition.

Comparison of reward effects on task 1 and task 2 performance

To test whether the reward prospect on task 1 affected the post-bottleneck stages of the task 1 processing chain in addition to the effects on the pre-bottleneck and bottleneck stages, we compared the size of the reward-related RT reductions in task 1 and task 2. For that purpose, we calculated an additional ANOVA across the RTs in the two tasks with the factors task (task 1 vs. task 2), SOA, and reward. The factor task did not reach significance, $F(1, 22) = 2.215$, $p = .151$, $\eta_p^2 = 0.091$, indicating no differences in processing speed between task 1 ($m = 708$ ms) and task 2 ($m = 682$ ms) RTs. The factor reward reached significance, $F(1, 22) = 20.235$, $p < .001$, $\eta_p^2 = 0.479$, reflecting shorter RTs in the reward ($m = 682$ ms) compared to the no-reward condition ($m = 708$

ms). We further obtained a significant main effect of the factor SOA, $F(1.460, 32.125) = 181.438$, $p < .001$, $\eta_p^2 = 0.892$.

Most decisively for the question of a reward-effect on the post-bottleneck stage in task 1, we obtained a significant interaction of the factors reward and task, $F(1, 22) = 19.683$, $p < .001$, $\eta_p^2 = 0.472$, which reflects the fact that the reward prospect led to a larger reduction of the RTs for task 1 than for task 2, m = 37 ms versus m = 21 ms, $t(22) = 3.049$, $p < .006$, for task 1 and task 2, respectively. Separate analyses at the separate SOAs indicated that reward prospect led to a larger reduction of RT1 compared to RT2 at each separate SOA, that is at SOA 100, 41 ms versus 27 ms, $t(22) = 2.694$, $p < .013$, SOA 300, 51 ms versus 38 ms, $t(22) = 3.049$, $p < .006$, and SOA 900, 18 ms versus −2 ms, $t(22) = 2.784$, $p < .011$, respectively. The larger amount of the reward-related reduction of RT1 compared to RT2 is consistent with the assumption that reward affected at least partially the motor processes of task 1 in addition to its effects on pre-and/or bottleneck stages in task 1; while the latter effects cause a shortening in the task 1 processing chain, which propagates via the bottleneck from task 1 to task 2, the reward leads to an additional shortening of the RT1, which is not reflected in corresponding RT2 effects.

We also found a significant interaction of the factors Reward × SOA, $F(2, 44) = 4.561$, $p <. 016$, $\eta_p^2 = 0.172$, demonstrating larger reward effects at SOA 100 ($m = 34$ ms) compared to SOA 900 ($m = 8$ ms), $t(22) = 2.048$, $p < .026$. In addition, we found a significant interaction of the factors Task × SOA, $F(1.037, 22.816) = 295.243$, $p < .001$, $\eta_p^2 = 0.931$. Naturally, task 2 was stronger affected by the SOA manipulation, than task 1. The interaction of the factors Task × Reward × SOA did not reach significance, $F(1.580, 34.763) = 0.542$, $p = .545$, $\eta_p^2 = 0.024$.

Discussion

In Experiment 1, the direct reward application to participants' task 1 performance, reduced both RT1 and RT2, which is reflected by the main effects of reward on RT1 as well as on RT2. The observation of an overadditive interaction of SOA and reward on RT2 reflects larger reward effects on RT2 at short compared to long SOA, which is consistent with the assumption that (at least part of) the reward effect propagated at short SOA from task 1 onto task 2, thus reducing RT2. This effect pattern demonstrates that the pre-and/or bottleneck processing stages of task 1 were shortened by the direct reward application to task 1 and that the observed reward effects on task 2 are the result of effect propagation via the bottleneck between tasks. A further hint for effect propagation stems from the analysis of the interdependency of the response times in task 1 and task 2 (Pashler & O'Brien, 1993), which we will discuss in more detail together with related findings in Experiment 2.

Importantly, we furthermore obtained results in line with the assumption that the reward prospect for task 1 performance results in larger reward effects on task 1 compared to task 2. This pattern was observed for each SOA level, providing evidence that not the entire task 1 reward effect was propagated from task 1 to task 2. Based on the predictions of the effect propagation logic (Pashler & Johnston, 1989; Schubert, 1999; Schweickert, 1978; Van Selst et al., 1999; Van Selst & Jolicoeur, 1997) these findings are consistent with the assumption that the prospect of reward for task 1 performance also affected the motor processes of task 1.

In the next experiment, we aimed to assess over which processing stages of task 2 the reward-related processing time reduction of pre-and/or bottleneck stages in task 1 will be propagated onto the task 2 processing chain. In other words, we asked which processing stages of task 2 are processed earlier due to the reward prospect onto task 1 processing.

Experiment 2

The aim of Experiment 2 was to identify the task 2 processing stage, which is processed earlier due to the reward prospect on task 1. For that purpose, we localized the bottleneck in the processing chain of a PRP task, while additionally, applying a reward prospect to task 1 processing. For the bottleneck localization, we applied a difficulty manipulation of the response selection stage of task 2, resulting in easy (compatible response mapping) and hard (incompatible response mapping) conditions (McCann & Johnston, 1992). Combining the locus-of-slack and effect propagation logics enabled us to distinguish whether the reward effect propagated over the central or peripheral bottleneck from task 1 to task 2 (Johnston & McCann, 2006; McCann & Johnston, 1992; Pashler & Johnston, 1989; Schubert, 1999; Schubert et al., 2008). For that matter, we will outline the predictions of the response selection difficulty manipulation and SOA on RT2 in particular, while the effects of reward and SOA will be discussed separately.

First of all, let us consider how the RT2 pattern should look like if a bottleneck at the response selection stage would interrupt the processing chain of task 2. In that case, the RT2 in the hard condition should be increased compared to the easy condition. This is observable in Fig. 4, which indicates additive effects of the response selection difficulty manipulation and SOA on RT2. In particular, in the hard condition, RT2 should be increased during short and long SOA by the *same* amount of additional time, since the additional time is added *after* the response selection bottleneck.

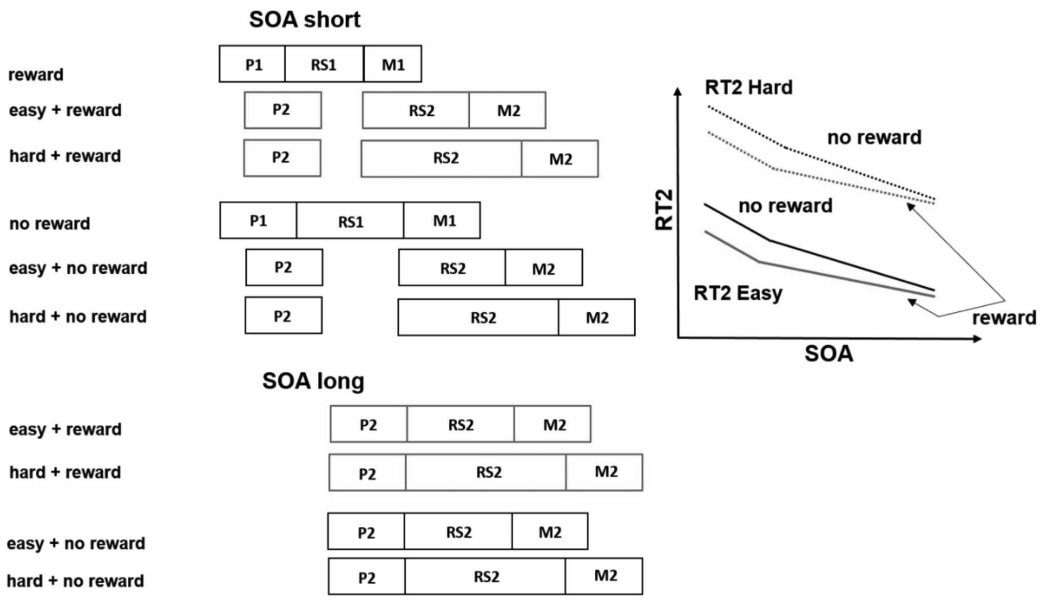

Fig. 4 Response selection bottleneck model including reward influencing the pre-and/or bottleneck and the post-bottleneck stages of task 1. Furthermore, the difficulty manipulation of the response selection of task 2 and RT2 predictions are depicted: Additive effects of the difficulty manipulation and SOA on RT2 should emerge, if the response selection stages of both tasks are processed serially, favoring the response selection bottleneck model (Easy = rule-based stimulus-response mapping; Hard = arbitrary stimulus-response mapping; Red indicates the rewarded conditions at short and long SOA respectively; P1 = perception stage of task 1; RS1 = response selection stage of task 1; M1 = Motor stage of task 1; P2 = perception stage of task 2; RS2 = response selection stage of task 2; M2 = motor stage of task 2)

Concerning the reward effects, we expect to replicate the findings from Experiment 1. That is, we expect to find that reward affects the processing stages before or at the bottleneck of task 1, leading to effect propagation on task 2 at short SOA. This can be seen in Fig. 4, which illustrates an overadditive interaction of SOA and reward on RT2. Such a reward effect pattern would be accompanied by the additive effects of SOA and response selection difficulty on RT2.

However, how should the RT2 pattern look like if a bottleneck would interrupt the processing chain at the response initiation stages between task 1 and task 2? If that were the case, we would expect an underadditive interaction of the response selection difficulty manipulation and SOA on RT2. As can be seen in Fig. 5, the additional time needed in the hard compared to the easy condition would be absorbed into the slack at short SOA, but not during long SOA. In particular, during long SOA, we would expect an increased RT2 for the hard compared to the easy condition, however, no differences between both conditions during short SOA on RT2. Regarding reward processing, we predict a replication of the results from Experiment 1. That is, reward should affect the processing stages before or/at the bottleneck of task 1, which would lead to effect propagation at short SOA on task 2, but not at long SOA. As can be seen in Fig. 5, we expect an underadditive interaction of response selection difficulty and SOA, as well as, an overadditive interaction of reward and SOA on RT2.

Important to note, that for both hypotheses about bottleneck location mentioned before we would expect reward effects on the motor stage of task 1, which are not propagated to task 2 (i.e., increased reward effects on task 1 compared to task 2).

Materials and methods

Participants

Twenty-four healthy participants (20 female; *mean* (*m*) *age* = *20.5* years) were invited to take part in the experiment after obtaining written informed consent. Participants could choose between 4 Euro or course credit as base payment. The experimental protocol conformed to the declaration of Helsinki. All participants were right-handed, German native speakers, and had normal or corrected to normal vision.

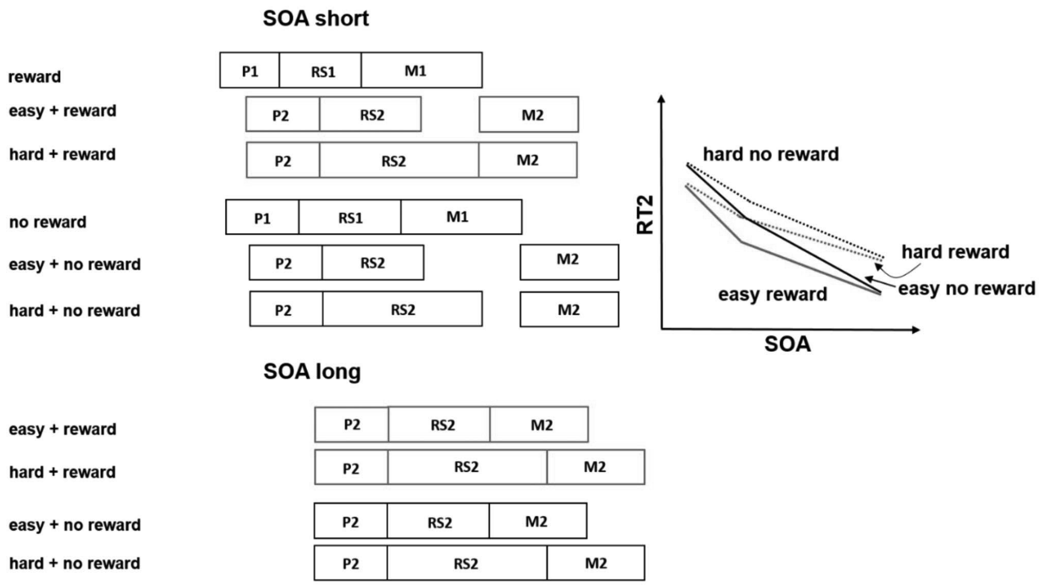

Fig. 5 Response initiation bottleneck model including reward influencing the pre-and/or bottleneck and the post-bottleneck stages of task 1. Furthermore, the difficulty manipulation of the response selection of task 2 and RT2 predictions are depicted: Underadditive effects of the difficulty manipulation and SOA on RT2 should emerge if the response selection stages of both tasks are processed concurrently, favoring the response initiation bottleneck model (Easy = rule-based stimulus-response mapping; Hard = arbitrary stimulus-response mapping; Red indicates the rewarded conditions at short and long SOA respectively; P1 = perception stage of task 1; RS1 = response selection stage of task 1; M1 = Motor stage of task 1; P2 = perception stage of task 2; RS2 = response selection stage of task 2; M2 = motor stage of task 2)

Apparatus and stimuli

The apparatus and the stimuli were the same as in Experiment 1. For the easy condition, we employed the same stimulus-response mapping as in Experiment 1. For the hard condition, we used an arbitrary (rather than a compatible) stimulus-response mapping for the visual task (task 2). In this condition, participants responded to the digits 1, 5, and 9 by pressing the '.', '-, and ',' buttons of a QWERTZ keyboard with the middle, ring, and index finger of their right hand. The difficulty manipulation was applied per block, resulting in easy and hard blocks, respectively. The trial sequence was identical to Experiment 1 with the exception that we included an additional SOA of 50 ms and adjusted the SOA of 100 ms to 150 ms. We aimed to investigate in more detail the time course of RT2 over the temporal overlap of both tasks. Participants received the feedback "Falsch" (German for wrong) for 500 ms if either one or two of their responses were erroneous. If their response to either target exceeded the maximal response duration, the feedback "Zu langsam" (German for too slow) was presented for 500 ms. For Experiment 2, the computations for the reward threshold in the easy and hard conditions were identical to the computations applied in Experiment 1.

Design and procedure

A three-factor within-subjects design with SOA and reward and compatibility as independent variables were used. Each block consisted of 36 trials resulting from the combination of 4 SOAs (50, 150, 300, 900 ms), 3 auditory stimuli (250, 500, 1000 Hz), and 3 visual stimuli (1, 5, 9). Reward was varied blockwise. In total, there were 16 blocks: 4 blocks of reward/easy mapping, and 4 blocks of reward/hard mapping. As well as, 4 blocks of non-reward/easy mapping, and 4 blocks of non-reward/hard mapping which resulted in an overall of 576 trials. The procedure was analogous to Experiment 1. After 24 single-task practice trials (12 for each component task) participants performed two runs of 36 trials of DT practice. The first run was the easy DT block and the second run was the hard DT block. The reward instruction, as well as the computation for the reward thresholds for obtaining a reward, were identical to Experiment 1.

Statistical analysis

We analyzed mean RTs and error rates separately for RT1 and RT2 using an ANOVA with the within-subjects factors SOA, reward, and task 2 difficulty. A significance threshold of 5% was used for all analyses. The *p* values of the ANOVAs were adjusted according to the Greenhouse-Geisser correction when necessary. For the RT analyses, trials with at least one erroneous response ($m = 10\%$) and outliers that deviated more than +/- 2.5 SD ($m = 2\%$) were excluded from the data set. Furthermore, trials were excluded that met the criterion of response grouping (RT2 – RT1 + SOA) < 200 (Miller & Ulrich, 2008).

Results

Task 1

Similar to Experiment 1, in Experiment 2 we found a significant main effect of reward on RT1, $F(1, 23) = 17.560$, $p < .001$, $\eta_p^2 = 0.433$. RT1 was shorter in the reward ($m = 758$ ms) compared with the no reward condition ($m = 812$ ms) (see Fig. 6a). Furthermore, we found a significant main effect of the factor compatibility on RT1, $F(1, 23) = 22.756$, $p < .001$, $\eta_p^2 = 0.497$, indicating shorter response times in the easy ($m = 764$ ms) than in the hard condition ($m = 806$ ms). In addition, we found a significant main effect of SOA on RT1, $F(1.819, 23) = 3.410$, $p < .047$, $\eta_p^2 = 0.129$, pointing to a slight grouping tendency of participants (Ulrich & Miller, 2008). In addition, we observed a significant interaction of the factors Reward × Compatibility, $F(1, 23) = 4.714$, $p < .040$, $\eta_p^2 = 0.170$. With a larger reward effect in the easy ($m = 64$ ms) compared to the hard ($m = 43$ ms) condition, $t(23) = 2.171$, $p < .040$.

Neither the interaction of the factors Reward × SOA, $F(3, 69) = 1.942$, $p = .131$, $\eta_p^2 = 0.078$, nor the interaction of the factors Compatibility × SOA, $F(3, 69) = 1.155$, $p = .333$, $\eta_p^2 = 0.048$, nor the three-way interaction of the factors Reward × Compatibility × SOA, $F(3, 69) = 0.321$, $p = .810$, $\eta_p^2 = 0.014$, reached significance.

For the error rates in task 1, we observed a significant effect of the factor compatibility, $F(1, 23) = 16.307$, $p < .001$, $\eta_p^2 = 0.451$, which was modulated by the SOA between tasks, SOA × Compatibility $F(3, 69) = 8.396$, $p < .001$, $\eta_p^2 = 0.267$. This reflects smaller compatibility effects ($m = -4\%$) at SOA 50 compared to SOA 900 ($m = 0.5\%$). Thus the error rates converged at SOA 900 in the hard and easy conditions.

Furthermore, we observed a significant effect of the factor reward, $F(1, 23) = 5.336$, $p < .030$, $\eta_p^2 = 0.188$. Participants committed fewer errors in the reward ($m = 7\%$) compared to the no reward condition ($m = 8\%$). In addition, we obtained a significant effect of the factor SOA, $F(1.894, 69) = 17.462$, $p < .001$, $\eta_p^2 = 0.432$. The error rates increased from SOA 900 ($m = 5\%$) to SOA 50 ($m = 10\%$).

Neither the interaction of the factors Reward × Compatibility, $F(3, 69) = 1.054$, $p = .315$, $\eta_p^2 = 0.044$, nor the

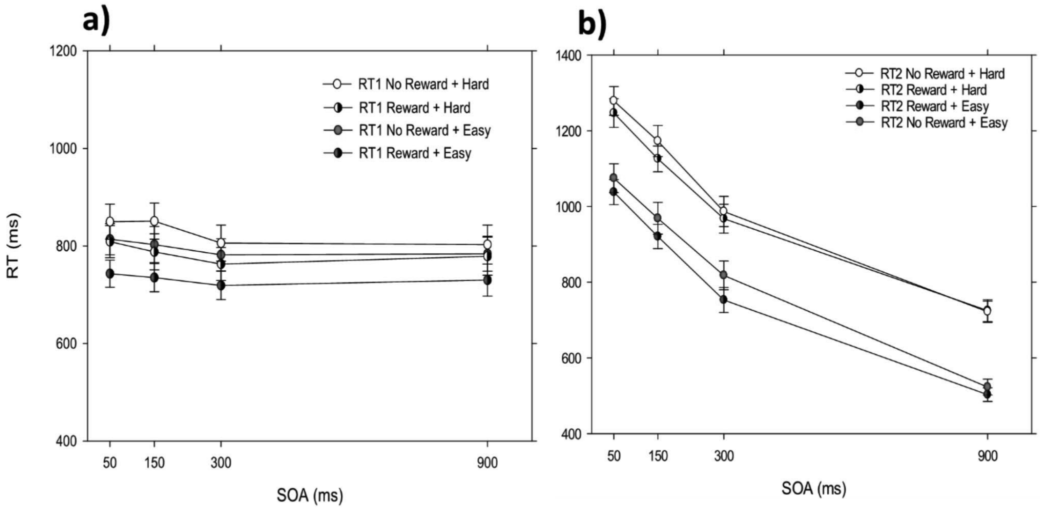

Fig. 6 Mean RT1 and RT2 as a function of SOA, reward, and compatibility for Experiment 2. Panel (**a**) represents task 1 performance and panel (**b**) represents task 2 performance. Error bars represent the standard error of the mean

interaction of the factors, Reward × SOA, $F(3, 69) = 1.404$, $p = .249$, $\eta_p^2 = 0.058$, nor the threeway interaction of the factors Reward × Compatibility × SOA, $F(3, 69) = 0.353$,, $p = .787$, $\eta_p^2 = 0.015$, reached significance.

Task 2

We found a significant main effect of the factor SOA, $F(3, 23) = 590.683$, $p < .001$, $\eta_p^2 = 0.963$. RTs increased from SOA 900 ($m = 618$ ms) to SOA 50 ($m = 1160$) ms indicating a typical PRP effect. Similarly to Experiment 1, we found a significant main effect of the factor reward on RT2, $F(1, 23) = 8.250$, $p < .009$, $\eta_p^2 = 0.264$ (see Fig. 6b). RT2 was reduced in the reward condition ($m = 910$ ms) compared with the no reward condition ($m = 943$ ms). This main effect was further specified by the Reward × SOA interaction, $F(2.149, 69) = 3.188$, $p < .046$, $\eta_p^2 = 0.122$. Pairwise comparisons revealed an overadditive interaction of SOA and reward on RT2 with a larger reward effect on task 2 at SOA 50 ($m = 34$ ms) compared with SOA 900 ($m = 8$ ms), $t(23) = 2.515$, $p < .019$. Furthermore, the reward effect was not different for SOA 150 and SOA 300, $t(23) = 0.352$, $p = .362$; similarly, the reward effect did not differ between SOA 50 and SOA 300, $t(23) = -0.664$, $p = 257$.

Furthermore, we observed a significant main effect of the factor compatibility, $F(1, 23) = 168.084$, $p < .001$, $\eta_p^2 = 0.880$. RT2 was shorter in the easy condition ($m = 825$ ms) compared with the hard condition ($m = 1028$ ms). Most important for the issue of the bottleneck location, we found no significant Compatibility × SOA interaction, $F(3, 69) = 2.686$, $p = .115$, $\eta_p^2 = 0.105$, which is consistent with the assumption that the SOA and the compatibility manipulation affected the RT2 in an additive manner and speaks against the assumption of a bottleneck at the response initiation stage in the current study. Instead, it points to serial scheduling of the response selection stages and to a response selection bottleneck.

Neither, the interaction of the factors Reward × Compatibility, $F(1, 23) = 2.686$, $p = .115$, $\eta_p^2 = 0.105$, nor the three-way interaction of Reward × Compatibility × SOA, $F(3, 69) = 0.831$, $p = .481$, $\eta_p^2 = 0.035$, reached significance.

For the error rates in task 2, we found a significant main effect for the factor compatibility, $F(1, 23) = 57.209$, $p < .001$, $\eta_p^2 = 0.713$. Participants committed more errors in the hard ($m = 13\%$) compared to the easy ($m = 8\%$) condition. We, furthermore, obtained a significant effect of the factor reward, $F(1, 23) = 4.392$, $p < .047$, $\eta_p^2 = 0.160$. The error rates were decreased in the reward ($m = 8\%$) compared to the no reward ($m = 10\%$) condition. In addition, we observed a significant interaction of the factors Reward × Compatibility, $F(1, 23) = 13.190$, $p < .001$, $\eta_p^2 = 0.364$. The compatibility effect was increased in the no reward ($m = 9\%$) compared to the reward ($m = 5\%$) condition, $t(23) = -3.632$, $p <. 001$. We also observed a significant interaction of the factors SOA × Compatibility, $F(2.221, 69) = 5.566$, $p < .005$, $\eta_p^2 = 0.195$. Pairwise comparisons revealed that this interaction was mostly driven by significant differences between error rates across different SOAs in the easy response selection condition, while the error rates hardly differed between SOAs in the hard response selection condition. In detail, the error rate in the easy condition at long SOA 900 ($m = 4\%$) was significantly reduced compared to that at SOA 50 ($m = 6\%$), and at SOA 300 ($m = 6\%$), both $ts(23) > -2.74$, $ps < 0.001$, while it was numerically but not significantly smaller than that at SOA 150, $p > .05$. In contrast, the error rate in the hard condition at SOA 900 ($m = 15\%$) was not significantly different from that at SOA 50 ($m = 12\%$), $t(23) = -1.7$, $p > .09$, and SOA 300 ($m = 12\%$), $t(23) = 0.824$, $p > .40$, while the difference approached significance compared to that at SOA 150, ($m = 11\%$), $t(23) = 2.02$, $p = .054$.

In sum, this pattern results in a smaller compatibility effect (hard minus easy) of error rates at short SOA ($m = 6\%$) compared to that at long SOA ($m = 11\%$), $t(23) = 2.939$, $p < .01$, which however, was especially caused by the significant reduction of error rates in task 2 at SOA 900 compared to all other SOAs in the easy response selection condition but not in the hard condition.

The factor SOA did not significantly affect the error rate, $F(3, 23) = 0.582$, $p = .629$, $\eta_p^2 = 0.025$ (Mattes et al., 2021; Strobach et al., 2015a). Neither the interaction of the factors Reward × SOA, $F(3, 69) = 1.811$, $p = .153$, $\eta_p^2 = 0.073$, reached significance, nor the three-way interaction of the factors Reward × Compatibility × SOA, $F(3, 69) = 0.310$, $p = .818$, $\eta_p^2 = 0.013$. The error rates for Experiment 2 can be found in Table 3.

Relationship between RT1 and RT2

The subsequent analysis focused on the relationship between RT1 and RT2 to investigate effect propagation from task 1 onto task 2 in more detail. As for Experiment 1, we predicted an interaction of SOA and quintile on RT2 indicating effect propagation from task 1 onto RT2 at short but not at long SOA. For this investigation, we relied on an approach established by Pashler and O'Brien (1993).

Figure 3b depicts that an increase in RT1 leads to a rise in RT2 as well. Most importantly, as SOA was reduced from 900 ms to 50 ms, the dependency of RT2 on RT1 increased. This observation was confirmed by the results of an ANOVA with RT2 as the dependent variable and the factors reward, SOA, and RT1 broken into quintiles (collapsed over two compatibility conditions for reasons of simplicity). Here, we obtained a significant interaction of the factors SOA × Quintile, $F(12, 276) = 44.63$, $p < .001$, $\eta^2 = 0.088$.

Table 3 Mean rates of errors for task 1 and task 2 in % (and standard deviation) from experiment 2 as a function of reward, SOA, and compatibility

	Experiment 2							
	Compatibility - Reward							
	easy - reward		easy – no reward		hard - reward		hard - no reward	
SOA	Task 1	Task 2	Task 1	Task 2	Task 1	Task 2	Task 1	Task 2
50	11.00% (9.21%)	6.71% (4.77%)	14.24% (7.61%)	5.79% (4.01%)	6.94% (6.60%)	11.22% (7.92%)	9.49% (6.99%)	13.19% (6.87%)
150	8.80% (7.49%)	6.13% (5.67%)	10.19% (5.83%)	5.43% (4.81%)	5.67% (6.37%)	9.84% (9.41%)	5.55% (4.85%)	12.96% (8.14%)
300	6.37% (5.01%)	6.02% (5.66%)	7.52% (5.46%)	6.83% (5.05%)	4.16% (4.18%)	10.88% (9.58%)	5.79% (4.70%)	14.00% (8.69%)
900	4.28% (5.24%)	3.82% (4.32%)	5.56% (4.56%)	4.62% (4.54%)	5.56% (4.10%)	12.27% (9.65%)	5.44% (4.81%)	17.59% (9.85%)

Table 4 Mean reward effects for task 1 and task 2 in ms (and standard deviation) from experiment 2 as a function of SOA and compatibility

	Experiment 2	
	Reward effects	
	Task 1	Task 2
SOA		
50	56 ms (14 ms)	34 ms (15 ms)
150	66 ms (16 ms)	47 ms (16ms)
300	53 ms (15 ms)	42 ms (14 ms)
900	39 ms (13 ms)	8 ms (11 ms)

Moreover, as depicted in 3b and following the results from Experiment 1 we obtained a significant interaction of the factors Reward × SOA, $F(3, 69) = 3.08$, $p < .033$, $\eta^2 = 0.002$. Such a result suggests larger reward effects at shorter compared to longer SOAs on RT2 and replicates the findings obtained from our previous analysis of task 2 performance across both experiments.

Furthermore, we found several further effects. Figure 3b shows increased reward effects for larger RTs compared to smaller RTs, this observation was confirmed by an interaction of the factors, Reward × Quintile, $F(4, 92) = 5.78$, $p < .001$, $\eta^2 = 0.004$. As in Experiment 1, such an effect could indicate that reward reduces lapses of attention, which usually occur during longer RTs.

In addition, we obtained a significant main effect of the factor SOA, $F(3, 69) = 554.96$, $p < .001$, $\eta^2 = 0.582$ and a main effect of the factor quintile, $F(4, 92) = 152.88$, $p < .001$, $\eta^2 = 0.390$. The factor reward reached significance, $F(1, 23) = 7.85$, $p < .010$, $\eta^2 = 0.007$, reflecting shorter RTs in the reward compared to the no-reward condition.

Comparison of reward effects on task 1 and task 2 performance

We, again as in Experiment 1, tested whether the reward prospect on task 1 affected the post-bottleneck stage of task (1) For that matter, we compared the reward-related RT reductions on task 1 and task (2) To this end, we calculated a separate ANOVA across the RTs with the factors task (task 1 vs. task 2), SOA, and reward (collapsed together for the two compatibility conditions for reasons of simplicity). The factor task reached significance, $F(1, 23) = 21.799$, $p < .001$, $\eta_p^2 = 0.487$, reflecting shorter RTs for task 1 ($m = 785$ ms) compared to task 2 ($m = 927$ ms). The factor reward reached significance, $F(1, 23) = 14.032$, $p < .001$, $\eta_p^2 = 0.379$, showing shorter RTs in the reward ($m = 834$ ms) compared to the no-reward condition ($m = 877$ ms). In addition, we obtained a significant effect of the factor SOA, $F(1, 23) = 247.948$, $p < .001$, $\eta_p^2 = 0.915$.

Most importantly, as in Experiment 1, we obtained a significant interaction of the factors Reward × Task, $F(1, 23) = 7.331$, $p < .013$, $\eta_p^2 = 0.379$, which expresses the observation of larger reward effects on RTs in task 1 ($m = 53$ ms) compared to task 2 ($m = 33$ ms), $t(23) = 2.708$, $p < .013$. An additional, analysis of the separate SOAs further showed that reward led to a larger reduction of RT1 compared to RT2, during each SOA, except at SOA 300. For SOA 50, 56 ms versus 34 ms, $t(23) = 2.708$, $p < .032$, SOA 150, 66 ms versus 47 ms, $t(23) = 2.730$, $p < .012$, SOA 300, 53 ms versus 42 ms, $t(23) = 1.097$, $p = .284$, SOA 900, 39 ms versus 8 ms, $t(23) = 2.621$, $p <. 015$, respectively. The increased reward-related reduction of RT1 compared to RT2 is in line with the assumption that the prospect of reward affected the motor processes of task 1 in addition to its effects on the pre-and/or bottleneck processing stages of task 1. While the former reward effect is not carried over from the processing chain of task 1 to task 2, the latter reward effect propagates via the bottleneck from task 1 to task 2, thereby reducing RT2.

In addition, we obtained a significant interaction of the factors Reward × SOA, $F(1, 23) = 2.926$, $p < .040$, $\eta_p^2 = 0.113$. Pairwise comparisons indicated larger reward effects at SOA 50 ($m = 34$ ms) compared to SOA 900 ($m = 8$ ms), $t(23) = 2.515$, $p < .019$. Furthermore, we obtained a significant interaction of the factors Task × SOA, $F(1.258, 28.940) = 454.893$, $p < .001$, $\eta_p^2 = 0.952$. This indicates that task 2 was strongly affected by the SOA application. The threeway interaction of Reward × Task × SOA did not reach significance, $F(3, 69) = 1.324$, $p = .273$, $\eta_p^2 = 0.054$.

Discussion

In Experiment 2, the reward application to task 1 led to reduced RT1 and RT2. Similarly, as in Experiment 1, we obtained an overadditive interaction of reward and SOA on RT2, which was accompanied by larger reward effects at short compared to long SOA on RT2. This pattern is consistent with the assumption that (at least part of) the reward effect propagated at short SOA from task 1 onto task 2, leading to a subsequent shortening of the RT2. This effect pattern indicates that the reward prospect to task 1 leads to a shortening of pre- and/or bottleneck-processing stages of task 1 and that the obtained reward effects on task 2 are the result of effect propagation over the bottleneck between tasks. As in Experiment 1, we obtained a robust interdependency of the response speed to task 2 on the response speed to task 1 at short SOA which was reflected by the interaction of quintile and SOA on RT2. In accordance with Pashler and O'Brien (1993), the interdependency of RT2 on RT1 was reduced with increasing SOA between tasks, as no bottleneck emerges in a PRP task with long SOA. Similar to Experiment 1, the results provide strong evidence for the assumption that effect propagation between task 1 and task 2 has taken part (at least at short SOAs), thus explaining how reward prospect on task 1 could lead to a reward-related reduction of task 2 processing time.

As a main question of Experiment 2, we investigated over which task 2 processing stages the reward-related processing time reduction in task 1 propagates into the processing chain of task 2. To tackle this question, we applied a difficulty manipulation of the response selection stage in task 2 and localized the bottleneck between tasks (McCann & Johnston, 1992; Pashler & Johnston, 1989; Schubert, 1999). The obtained pattern of results showed additive effects of the difficulty manipulation and of the SOA on RT2, which is consistent with the assumption that the bottleneck occurred at the response selection (McCann & Johnston, 1992; Schubert, 1999) and not at the motor response stage (Keele, 1972; Kieras & Meyer, 1997; Mittelstädt et al., 2022). This, in turn, indicates that the reward-related processing time reduction in task 1 propagated from the pre- and/or bottleneck stages of task 1 via a response selection bottleneck onto the processing chain of task 2, thus leading to an earlier onset of the response selection stage of task 2.

Please note that we obtained a significant interaction of the factors SOA x compatibility on the error rates of task 2, which might be interpreted as compromising the conclusion of a response selection bottleneck emerging in Experiment 2[2]. However, in our view, the observed interaction does not compromise the interpretation of the additive RT2 effects of SOA and compatibility as evidence for serial response selection processing in the two tasks. If the significant SOA x compatibility error rate interaction had been caused by parallel response selection processes at short SOA, then one should have expected improved task 2 processing, i.e. a decreased error rate, at short SOA compared to long SOA especially for the hard condition. This is so because the additional processing demands for the hard response selection should have been absorbed into slack, thus, causing more success when selecting the required response alternative compared to the situation at long SOA where no absorption of additional response selection demands is possible; please note, if the RTs have not benefited in the hard response selection condition at short SOA, then the improvement should have been expressed in the error rates. However, the error rate in the hard condition at short SOA 50 was not different from that at SOA 900 and it was larger in the hard compared to the easy response selection (SOA 50), which opposes the idea that any additional response selection processes had been absorbed into slack at short SOA. Instead, the particular error rate pattern across different SOAs suggests that the SOA x compatibility interaction was driven by a decreased error rate especially in the easy response selection condition at long SOA compared to all other SOAs. Various reasons could be proposed for explaining this pattern. For example, it would be consistent with the assumption that participants could more successfully prepare for task 2 in the easy response selection condition at long SOA compared to the other SOAs, where the two task chains are temporally overlapping to a larger degree. Since at the same time, the error rates in the hard response selection condition did not differ across SOAs, we believe that this is a more plausible explanation for the observed SOA x compatibility error rate interaction than the assumption of parallel response selection processes at short SOA (see also Schubert, 1999).

As a further important finding, we observed larger reward effects on RT1 compared to RT2 at each SOA level (except for SOA 300). This suggests that reward effects were located on pre-bottleneck and/or bottleneck stages and, in addition, at the motor stage of task 1. This is so because according to

[2] This was proposed by an anonymous reviewer.

the effect-propagation logic any change of RT1 processing time, which occurs *after* the bottleneck in task 1, i.e. at post-bottleneck stages, would not result in corresponding RT2 changes. The observed pattern of a larger reward-related reduction of RT1 compared to RT2 is consistent with the assumption that part of the reward-related task 1 reduction occurred at post-bottleneck stages. Probably, the reward prospect on task 1 leads to improved execution of the task 1 motor response, which is expressed by shorter motor execution occurring after the bottleneck and leading to a shortening of the RT1 which is not expressed in a corresponding RT2 shortening.

General discussion

The present study investigated the effects of a direct reward application to task 1, as well as, the question of which processing stages in the DT processing chain are affected by the prospect of reward. For this purpose, in Experiment 1, we applied a reward manipulation to participants' task 1 performance in a PRP task situation. The results showed shorter RT1 in the reward compared to the non-reward condition across all SOA conditions. In addition, we also observed an overadditive interaction of SOA and reward onto RT2. According to the effect propagation logic, these results are consistent with the assumption that the reward prospect onto task 1 leads to a shortening of task 1 processes and that (at least part of) the processing time shortening is transmissed via the bottleneck onto task 2 processing time, and, thus, spills over to the non-rewarded task 2. In addition, reward on task 1 led to significantly larger reward effects on task 1 compared to task 2, which is consistent with the assumption that part of the reward effect affected those processes of task 1, which are located after the bottleneck and the reduction of which cannot be propagated to the task 2 chain.

In Experiment 2, we specified the processes of task 2, over which the reward-related task 1 processing advantage is transmissed onto the task 2 processing chain. As a result, the application of the locus-of-slack technique provided findings consistent with the assumption that the reward-related reduction of task 1 processing time is transmissed via the response selection processes from task 1 to task 2.

The localisation of reward-related improvement in Task 1 processing in dual tasks

The current results are consistent with the assumption that the prospect of reward on task 1 affected both, the processes before and/or at the bottleneck and the post-bottleneck processes in task 1, i.e. the motor stages. The reward-effect localization at these processing stages in a DT situation extends the findings of other studies, which showed reward-related improvements of these processes but in single-task situations. For example, several studies (Asutay & Västfjäll, 2016; Engelmann, 2009; Hübner & Schlösser, 2010; Kiss et al., 2009) indicated that the prospect of reward can improve early attentional and/or perceptual processes in choice RT single tasks. For the specific case of auditory perceptual processing (as the current task 1), Asutay and Västfjäll (2016) showed that reward-dependent attentional learning can affect the attentional selection and consequently the perceptual acuity in an auditory detection task. In particular, the authors asked participants to discriminate target tones from control tones while associating different reward probabilities with the control tones in a reward-learning phase of the experiment. The results showed that the perceptual sensitivity concerning tone discrimination changed tremendously depending on the reward probabilities during the learning period. The authors concluded, that the motivational value biased the auditory attentional selection of the auditory stimuli during task processing.

Thus, it is conceivable that in the current auditory task 1 situation, the prospect of reward resulted in increased attentional effort leading to enhanced quality of the auditory sensory processing. Such an effect localization is also supported by the current observation that the prospect of reward improved the accuracy of task 1 performance, which might reflect an increased rate of evidence accumulation in the reward condition, improving accuracy, as well as, RTs, in contrast to the non-reward condition. The resulting shortening in task 1 processing time would be propagated via the bottleneck to the processing time of task 2 and lead to its subsequent shortening. Important to note that an additional reward-effect localization at the task 1 response selection processes would also explain the observed propagation of the reward effect from task 1 to task 2 processes. An improvement of the response selection would be consistent with the results of several studies (Etzel et al., 2016; Kennerley & Wallis, 2009), which have shown that reward prospect may influence the updating and maintenance of task-relevant information in working memory, thus reducing the time for the response selection stage. In sum, the current findings are consistent with a localisation of a considerable portion of the reward effects on the joint processing time for perception and response selection in task 1, which explains the reward effect propagation to the task 2 processing time at short SOA.

Additionally, part of the task 1 reward effects are localized outside the pre-bottleneck and bottleneck processing time, which, to the best of our knowledge, is a new observation for the case of DT situations (see Langsdorf et al., 2022). In the current study, the task 1 reward prospect reduced the RT1 to a larger extent than RT2, which indicates that not all processing time reduction in the task 1 chain was transmissed to the task 2 chain. Since the results of Experiment 2 indicated that the bottleneck between tasks was located at the response selection, we locate the particular processing time that is not transmissed to the task 2 time, to the post-bottleneck processes, i.e. the motor processing of task 1.

The observation of a larger reward effect on task 1 compared to task 2 is in contrast to the effect pattern obtained by an earlier study of our group (Langsdorf et al., 2022). One possibility for the discrepancy between the findings of the current study and that of Langsdorf et al. (2022) is the different assignment of the reward prospect on task 1 in the current study and on task 2 in Langsdorf et al. (2022), which might have changed task processing and the resulting pattern of motivational influences between the two studies. While in the current study, the reward prospect was related to the task 1 processing chain, the reward prospect in Langsdorf et al. (2022) was related to the bottleneck-interrupted task 2 processing chain. Therefore, the reward prospect in the current study could have led to a direct influence on the task preparation even on motor processes, which was prevented in the Langsdorf et al. (2022) study because of the bottleneck.

The assumption that the reward prospect on task 1 might have caused a direct impact on motor stages only in case that the task processing is not interrupted by a bottleneck would be consistent with recent findings of neurophysiological investigations focussing on the neural activation during the performance of PRP tasks with neuroimaging methods (Stelzel et al., 2008; Wang et al., 2023). For example, Wang et al., 2023 showed increased functional connectivity between sensory areas and the default-mode network indicating that the neuronal processing of task 2 is suspended during task 1 processing in a PRP-like DT situation. In addition, Stelzel et al. (2008) could show that bottleneck processing in task 2 decreased the functional connectivity between sensory areas and later processing areas in task 2 at short compared to long SOA, which causes the RT2 to increase at shorter compared to long SOA. Thus it is conceivable that the improved reward-effect transmission to the motor stages of task 1 has occurred in the current study but not in the study of Langsdorf et al., 2022 because, in the latter study, the reward prospect was related to task 2, i.e. to the suspended task of the PRP situation.

Reward effects in rewarded and non-rewarded tasks in multiple task situations

The current findings allow for a more elaborated discussion of the occurrence of reward-related spillover effects from rewarded to non-rewarded tasks in DT situations, which can also contribute to the understanding of the mixed evidence on reward-related spillover effects reported in other studies (e.g., Kleinsorge & Rinkenauer, 2012; Rieger et al., 2021; Umemoto & Holroyd, 2015).

In the previous study of Langsdorf et al. (2022) and the current investigation, the application of task-selective reward associations enabled us, to further elucidate spillover effects from the rewarded to the non-rewarded task in DT situations. In particular, we obtained increased reward effects for the rewarded task in contrast to the non-rewarded task across both studies, while also obtaining reward-related task improvements for the non-rewarded task. Importantly, the chronometric approach in combination with a PRP paradigm enabled the conclusion that the temporal overlap of the processing chains of both component tasks is crucial for the emergence of spillover effects, as indicated by the effect propagation between tasks at short SOA. In contrast, for the long SOA condition, no or less reward-related spillover effects occurred between both tasks. Therefore, the current study and the study of Langsdorf et al. (2022) provided conclusive evidence under which DT conditions reward-related spillover effects from the rewarded to the non-rewarded task will emerge.

The current findings extend previous results from a study by Rieger et al. (2021) who compared reward-induced preparation effects across DT paradigms. For the case of a PRP-like DT paradigm, the authors applied either a high reward to task 1 and a low reward to task 2, or vice versa. The authors reported that a high reward prospect to task 1 (compared to low reward prospect) led to reward effects on task 1 performance; whereas a high reward prospect to task 2 (compared to low reward prospect) did *not* result in reward effects on task 2 performance. The authors suggested that the *absence* of reward-related task 2 improvements in the PRP-like DT paradigm could be caused by the need to coordinate two motor responses, which might have impeded the reward-induced improvement of task 2 preparation.

An alternative reason for the absence of reward-related task 2 improvements might result from the consideration of the way how participants perceived a reward prospect on task 2 performance and the selection of trials for the analysis in Rieger et al. (2021). In particular, our findings demonstrated that the reward prospect to task 2 performance, leads to a shortening of the task 1 processing stages before or/at the bottleneck and this, leads subsequently, via effect propagation over the central bottleneck to a shortening of the task 2 processing time, thus, reducing RT2 (Langsdorf et al., 2022). However, Rieger et al. (2021) selected for their analysis of task 2 performance specifically those trials, in which participants did *not* respond to task 1 but only to task 2. This, however, causes that a potential reward effect can not be transmissed from task 1 via the central bottleneck mechanism onto the task 2 processing chain, as no first response was made; in other words, this might prevent the detection of a spillover of reward effects between tasks in the PRP DT task.

The current findings and those of Langsdorf et al. (2022) support an assumption according to which the preparation of two motor responses in the PRP task does NOT prevent the emergence but represents a decisive precondition for the emergence of a spillover of the reward effect on the non-rewarded task 2. The need to process two tasks in an overlapping manner with a bottleneck connecting the processing streams seems to represent a precondition for the transmission of reward-related task improvements between tasks in overlapping DT situations.

In that respect, the results of Kleinsorge and Rinkenauer (2012) need to be discussed who showed reward-related spillover effects to a non-rewarded task in a cued task-switching paradigm, in which the two tasks are processed sequentially but not in an overlapping manner. In particular, participants executed parity or magnitude judgments on digit stimuli, for which the performance in *one* of the tasks was rewarded, while the other task was *not* rewarded for the entire experiment, which resulted in a constant task-reward association for the whole experiment. Before digit onset, a task cue signaled to the participants which task to execute, while in some trials an additional cue signaled whether or not the current trial is a reward trial. Consequently, in some trials, the prospect of reward was signaled, but the possibility of receiving the reward was conditional upon whether the rewarded or the non-rewarded task should be executed. The authors reported improved task performance for the rewarded task if the cue signaled the prospect of reward compared to when no reward was signaled. However, task performance for the non-rewarded task was also improved, particularly, in those situations in which the cue signaled the prospect of a reward compared to no reward cues. Consequently, the cue signaling potential reward led to improved task performance for the rewarded task *and* the non-rewarded task as well. The authors suggested that the prospect of reward (as signaled by the cue) led to phasic alertness resulting in the mobilization of increased processing resources, which spilled over to improve task performance even in the non-rewarded task.

The conjoint discussion of the results on reward-related spillover effects in the PRP DT and in cued task-switching situations enables a further specification of the task conditions for which reward-related spillover effects are likely to emerge. The results of Kleinsorge and Rinkenauer (2012) suggest that the temporal coincidence of processes evoked by the reward cue *with* the task preparation to the non-rewarded task leads to the mobilization of increased processing resources that spilled over to improve performance in that (by definition) non-rewarded task. In fact, the results of the current study showed that the temporal overlap of the rewarded task 1 and the non-rewarded task 2 is important for enabling the transmission of reward effects between these tasks over the bottleneck, with increasing reward effects with short compared to long SOA, i.e. with larger compared to less temporal overlap. As a result, this indicates that a sufficient amount of temporal overlap of the reward prospect (i.e. either cued or task-related) with the processes in the preparation of the non-rewarded task represents an important precondition for the emergence of reward-related spillover effects in multiple task situations. Future studies should specify the temporal limitation for which an optimized reward-induced preparation can be achieved, i.e. by determining the optimal time range necessary for efficient spillover effects between rewarded and non-rewarded task processes.

Additionally, the emergence of reward-related improvements in DT situations is modulated by strategic influences resulting from the assignment of the specific reward association by the participants. In more detail, the comparison of the size of the reward effects in Langsdorf et al. (2022) and the current study indicates that depending on whether the prospect of reward was either associated with task 1 or task 2 performance, the magnitude of the reward effect was increased for the rewarded task compared to the non-rewarded task. Such an effect pattern indicates that participants do not handle the two component tasks as completely interrelated tasks but as two tasks with different and separate reward values, which leads to different outcomes of the reward effects in dual-task situations.

The differences in reward effects across both studies could be indicative of a strategic processing adjustment for the allocation of mental effort, to maximize rewarded task performance in order to receive a reward (Kool & Botvinick, 2018). In particular, if task 1 is rewarded but not task 2 (as is the case in the current study), participants allocate increased mental effort to the execution of task 1, which in turn results in larger reward effects on task 1 compared to task 2. On the contrary, if as was the case in Langsdorf et al. (2022) task 2 but not task 1 is associated with the prospect of reward, then participants should first also focus on the execution of task 1, because a fast task 1 execution would result in fast task 2 execution, as well, because of the bottleneck mechanism. The observation of a larger reward effect on task 2 indicates that participants maximized their allocation of mental effort by especially attending to task 2 processing.

From a broader perspective, the current findings, drawing on a careful application of chronometric inferences in overlapping DT situations, allow us to extend former conclusions about reward-cognition interactions in sensory-motor RT tasks. While earlier studies have often mainly focussed on issues like the reward-related modulation of e.g. conflict processing, attention, or cognitive flexibility (e.g., Fröber & Dreisbach, 2016; Jimura et al., 2010; Kiss et al., 2009; Krebs et al., 2010; Locke & Braver, 2008), the current results promote a different perspective; namely to analyze in detail and to compare the magnitude of the reward-related task improvements occurring across and between the separate tasks in multiple task situations. The application of analytic tools like the locus-of-slack technique (Pashler & Johnston, 1989; Schweickert, 1978) in combination with a careful manipulation of the reward prospects to different task streams might be fruitful for further pinpointing the question of task-specific reward effects and their transmission to the non-rewarded task chain.

Reward effects and the question of parallel versus serial processing in dual tasks

An important further aspect is the question of serial versus parallel processing of the response selection processes in the two tasks and whether or not the application of monetary reward leads to a change in this architecture. Note that authors like Meyer and Kieras (1997) (see also Salvucci & Taatgen, 2008) propose that participants may engage in more daring dual-task coordination strategies leading to more parallel processing of the response selection processes under certain conditions, such as monetary reward. Other authors assume a central bottleneck causing serial scheduling of the response selection processes in the two tasks for structural reasons of a limited capacity for response selection processes (Pashler, 1994; Welford, 1959).

The current application of the response selection difficulty manipulation with the locus-of-slack technique in Experiment 2 allows us to test whether or not the application of reward has changed the serial scheduling of the response selection processes in the two tasks (McCann & Johnston, 1992). Importantly, the current results indicate that both response selection stages were processed serially constituting a central bottleneck and that the application of reward did not lead to more parallel processing of the central stages as could be assumed if considering the possibility of a strategic bottleneck processing in overlapping task processing (Meyer & Kieras, 1997; Salvucci & Taatgen, 2008). Instead, the current findings suggest that the central bottleneck processing has not changed due to reward prospects onto task 1 processing. This complements the findings of Langsdorf et al. (2022), who also showed that reward prospect onto task 2 processing does not change the bottleneck localization in a DT situation either. Thus, the combined consideration of the results of both studies suggests that monetary reward on either task 1 or task 2 improves DT processing, but does not lead to a change in the serial scheduling of response selection processing in overlapping dual tasks.

This is also in line with a study by Fischer et al. (2018) who reported improved serial processing in a PRP task situation due to reward prospect and used a different methodology in order to investigate parallel processing in a DT situation. In detail, the authors investigated the influence of reward prospect on the size of the backward compatibility effect (BCE), which reflects an influence of the congruence between the motor response in task 2 and task 1, with larger RT2 and RT1 in incongruent compared to congruent conditions. This can be explained by the occurrence of response activation processes for task 1 and task 2 motor responses, which operate simultaneously during the refractory period of both tasks (Hommel, 1998; Lien & Proctor, 2002; Schubert et al., 2008). Importantly, the authors observed a reduced BCE in the reward compared to the non-reward condition and interpreted this with the conclusion of a reduced amount of simultaneous response activation and an increased degree of serial DT processing. Thus, these findings just as the findings observed with the locus-of-slack technique in the current study do not support an assumption that reward prospect increases the amount of parallel processing of response selection in DT situations.

Conclusion

We provided evidence that the prospect of reward for task 1 results in effect propagation over the central bottleneck from task 1 to the non-rewarded task 2, leading to an earlier onset of the response selection stage of task 2. Thus the effect propagation logic is applicable for the interpretation of the reward-related spillover effect between tasks. While the prospect of reward improved RT1 and RT2, the serial scheduling of the response selection stages was not altered. Importantly, parts of the reward effect were not propagated to task 2 thus affecting motor-related processes of task 1. As a result, the prospect of reward for task 1 performance led to increased reward effects on task 1 compared to task 2.

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Declarations

Competing interests The authors declare no competing interests.

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

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Investigation of reward effects in overlapping dual-task situations

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ABSTRACT

In dual-task (DT) situations, performance in reaction time and error rates decrease compared with single-task situations. These performance decrements are usually explained with the serial processing at the response selection stage constituting a bottleneck. Evidence for this assumption stems from the observation that response times for the second task (task 2; RT 2) increase with decreasing stimulus-onset asynchrony (SOA). In this study, we investigated the effect of reward on bottleneck processing in DTs. In Experiment 1, we addressed two questions. First, does reward provided for task 2 performance affect task 2 performance, or does it affect task 1 performance? To conclude whether reward affected task 2 or task 1 performance, we relied on the psychological refractory period paradigm (PRP) as a chronometric tool. Second, we asked for the locus of the reward effect within the DT stream. We demonstrated shorter RTs in task 1 in a rewarded compared with an un-rewarded condition indicating reward affected task 1 processing. Furthermore, this reward effect is propagated onto task 2 at short SOA suggesting that the locus of the reward effect can be pinpointed before or at the bottleneck of task 1. In Experiment 2, we tested for the locus of the effect propagation onto task 2. To this end, we implemented an additional difficulty manipulation of the response selection of task 2 and found that the reward effect is propagated from task 1 onto the response selection stage of task 2.

1. Introduction

Multitasking is demanding for the cognitive system. In multitasking situations, our performance is impaired compared to when we perform the same tasks separately. The underlying processes have long been investigated using dual-task (DT) paradigms such as the paradigm of the psychological refractory period (PRP). In those DT paradigms, participants perform two temporally overlapping choice reaction time (RT) tasks, which usually leads to decreased performance in processing times and/or error rates compared to single-task situations (Pashler, 1994; Schubert, 1999). The resulting DT costs are often explained by the assumption of a *response selection bottleneck*, which postulates the serial execution of central processing stages for both tasks. Irrespective of the ongoing debate about the nature of the bottleneck being strategical or structural (Kieras & Meyer, 1997; Pashler, 1994), different factors and interventions have been identified that modulate bottleneck processing in DT situations, such as training (Ruthruff, Van Selst, Johnston, & Remington, 2006; Strobach, Salminen, Karbach, & Schubert, 2014a; Strobach & Schubert, 2016) or different input and output modality pairings (Hazeltine, Ruthruff, & Remington, 2006; Stelzel, Schumacher, Schubert, & Mark, 2006). A further relevant question in this vein of research is whether and how reward can modulate bottleneck processing.

So far, the evidence for reward modulating DT performance is mixed (Fischer, Frober, & Dreisbach, 2018; Han & Marois, 2013; Yildiz, Chmielewski, & Beste, 2013). Some studies reported enhanced DT performance due to reward, as reflected by reduced RTs and error rates (Charron & Koechlin, 2010). Further studies reported reduced between-task interference of the first and the second task (task 1; task 2) as well as reduced response times for task 1 (RT 1) for DT situations in rewarded versus un-rewarded blocks (Fischer et al., 2018). In contrast, however, a further DT study of Yildiz et al. (2013) revealed decreased DT performance (longer RTs) in a rewarded compared to an un-rewarded condition, if the task order was unpredictable. In sum, data on reward and its effect on DT performance are inconclusive. Furthermore, the mechanisms underlying the effects of reward on DT performance are still underspecified. In particular, it is unclear how the perceived reward influences participants' processing and which of the two tasks is affected if reward is administered in a DT situation. In addition, it remains an open question which processing stages are affected by reward. Does

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reward enhance perceptual processing of the target stimuli, or does it rather affect response selection or the instantiation and execution of a motor response or a combination of these processes?

This study aimed to tackle these issues and elucidate the possible effects of reward on performance in DT situations. As a first question, we were interested in whether participants' perceived reward influences task processing of a task that is processed to a larger extent after the bottleneck and how that affects DT performance. To this end, we provided reward for fast and correct performance for task 2 but not for task 1 in a PRP DT situation. As will be outlined below, a PRP DT situation consists of one component task processed before (task 1) and one task with most processes operating at or after the bottleneck (task 2). This specific task scheduling makes it important to ask, what happens if reward is associated with task 2 processing although this processing is mostly executed after the processing of task 1 and, thus, after the bottleneck. For this situation, it is unclear how the reward application to task 2 affects the perceived reward of participants within the DT situation. In other words, the perceived reward of task 2 could either influence the participant's processing of task 2 or, alternatively, the participant's processing of task 1 could be affected or the processing of both tasks might be influenced. To our knowledge, so far, no study has investigated whether and how the application of reward to the task processed mainly after the bottleneck affects participants' task processing. Therefore, it is an open question how the perception of reward will influence the task processing of the participants.

In addition, the exact locus of the reward effect within the processing chain deserves further consideration. It is unclear whether reward affects perceptual processes, response selection, or motor-related processes. Preliminary evidence for the potential locus of the reward effect comes mostly from single-task studies. There have been reports that reward can improve performance in a plethora of different paradigms, such as spatial cueing, negative priming, and the Erikson flanker task (Dambacher, Hübner, & Schlösser, 2011; Engelmann, Damaraju, Padmala, & Pessoa, 2009; Engelmann & Pessoa, 2007; Engelmann & Pessoa, 2014; Hübner & Schlösser, 2010; Kiss, Driver, & Eimer, 2009). Several of these studies indicated that early attentional and perceptional processes, rather than later processing stages, are affected by reward (Dambacher et al., 2011; Engelmann & Pessoa, 2014; Hübner & Schlösser, 2010). However, similar results indicating effects of reward on early processing stages in DT situations are lacking. Thus, one aim of this study was to test whether reward affects pre-bottleneck, bottleneck, or post-bottleneck stages in DT situations.

To shed further light on the perception of reward and its influence on the processing of tasks in DT, as well as the locus of the reward effect in DT situations, in Experiment 1, we used the PRP paradigm and applied the *locus of slack* (Schubert, 1999; Schweickert, 1978) and the *effect propagation* logic (Janczyk, Humphreys, & Sui, 2019; Pashler & Johnston, 1989; Van Selst & Jolicoeur, 1997; Van Selst, Ruthruff, & Johnston, 1999). In the PRP paradigm participants perform two choice RT tasks that are presented with varying stimulus-onset asynchrony (SOA). The processes of the component tasks can be subdivided into a perceptual stage, a response selection stage, and a motor stage. As a typical finding, the response time to task 2 (RT 2) increases as SOA decreases, whereas the SOA does not affect RT 1. To account for these results, the response selection bottleneck model assumes a bottleneck at the response selection stage. According to this view, the response selection for both tasks is processed sequentially. Consequently, at short SOA, the bottleneck and the post-bottleneck stages, i.e. response selection and the subsequent motor stage of task 2, have to wait until the processing of the response selection of task 1 has finished. This results in a slack time which increases RT 2. At long SOA, in contrast, response selection and the subsequent motor stage of task 2 can occur without additional slack time resulting in shorter RT 2.

For the present study, we applied a reward manipulation on task 2 and compared the condition of a rewarded with the condition of an unrewarded DT situation, assuming a shortening of RTs in the rewarded in contrast to the un-rewarded condition (Charron & Koechlin, 2010; Dambacher et al., 2011; Fischer et al., 2018; Hübner & Schlösser, 2010). As can be seen in Fig. 1, different predictions concerning the effects of reward and SOA on RT 2 are conceivable for the case that a reward manipulation affects the processing of task 2 by the participants. These predictions differ with respect to the assumption that reward affects pre-bottleneck OR bottleneck/post-bottleneck stages of task 2. In case that the reward manipulation would affect the pre-bottleneck stages in task 2 we should observe an *underadditive interaction* of SOA and reward on RT 2. This is so because the reward-related reduction of the processing time would occur at a processing stage located before the bottleneck. In that case, any change of the processing time duration of the stage occurring before the bottleneck (pre-bottleneck) would be absorbed into slack emerging before the bottleneck-stage in task 2. Therefore, the potential amount of a reward-related reduction of processing times for the perception in task 2 (i.e. in the pre-bottleneck stage in task 2) would NOT affect the RT 2 at short SOA in the rewarded compared with the un-rewarded condition. However, at long SOA, with no slack time, reward would affect the onset of the subsequent response selection stage, resulting in reduced RT 2 in the rewarded compared to the un-rewarded condition. As a net effect, we should observe an RT 2 pattern, in which reward leads to a larger effect in the rewarded compared with the un-rewarded condition at long SOA compared to short SOA, which describes the underadditive interaction of SOA and reward on RT 2 (see Fig. 1a). Please note, the particular relationship of RT 2 and SOA for the underadditive interaction. In detail, RT 2 of the rewarded and the un-rewarded condition, will, theoretically at shorter SOAs, decrease and not differ from each other until SOA is increased to the point where no more slack time results. After that point, RT 2 for the rewarded and unrewarded condition should diverge. Deviations from this optimal time course of the underadditive RT 2 x SOA interaction can be expected if the SOA variation does not cover gapless the complete overlapping time of task 1 and task 2, with some parts of the time curves, interpolated if only a few SOAs can be administered (see e.g. Reimer, Strobach, Frensch, & Schubert, 2015; Schubert, Fischer, & Stelzel, 2008). In sum leading to a discontinuous relationship between RT 2 and SOA for that particular case.

As an alternative, the reward manipulation might affect bottleneck and/or post-bottleneck processes in task 2 (i.e. response selection or motor stages). This locus of the reward effect would be reflected by *additive effects* of SOA and reward on RT 2. According to a number of authors (Pashler, 1994; Schubert, 1999), the manipulation of the processing time for stages occurring after the slack time should lead to an equally-sized effect on RT 2 at the different SOA conditions because the effect manipulation cannot be absorbed into the slack time. Consequently, if reward would affect bottleneck and/or post-bottleneck stages in task 2 we should observe effects of reward at short AND at long SOA and the amount of the reward effect should not differ between the different SOAs (see Fig. 1b).

Importantly, the situation for the predictions about how the perceived reward will affect participants' processing of a given task is even more puzzling and the expected RT pattern is more multifaceted than only focusing on reward effects at task 2. This is because there is accumulating evidence that participants represent DT situations as a whole, combining both component task representations within one higher-order task representation (Hirsch, Nolden, & Koch, 2017; Kübler, Reimer, Strobach, & Schubert, 2018; Kübler, Soutschek, & Schubert, 2019; Kübler, Strobach, & Schubert, 2021; Schubert & Strobach, 2018; Strobach, Salminen, Karbach, & Schubert, 2014b). Several studies have shown that subjects prepare a combined processing of the task 1 and task 2 chain at the beginning of a DT trial. For example, it has been shown that manipulations of the difficulty for task 2 affect the time for preparing the whole DT situation, which results in effects on the processing time of task 1 (Janczyk, Pfister, Hommel, & Kunde, 2014; Miller, 2006; Schubert & Strobach, 2018). Thus, the perception of reward might not selectively affect task 2 processing but, instead, it might be already

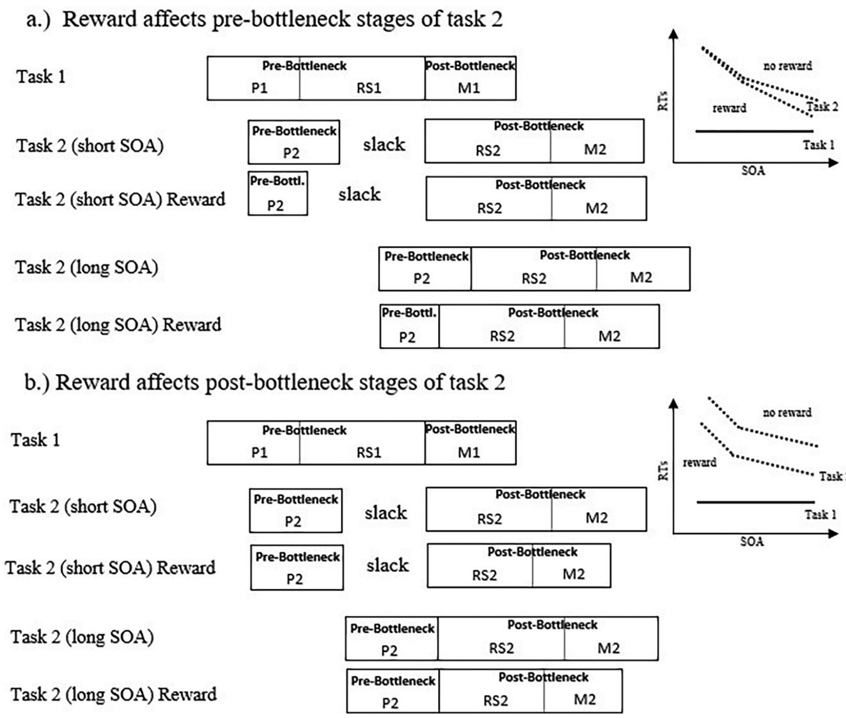

Fig. 1. Perceived reward influences processing of task 2 and RT predictions: a) Processing of task 1 and task 2 if participants' perceived reward influences processing of the pre-bottleneck stage of task 2. Resulting in an underadditive interaction of reward and SOA on RTs. b) Processing of task 1 and task 2, if participants perceived reward influences processing of bottleneck and/or post-bottleneck stages of task 2. Resulting in additive effects of reward and SOA on RTs. (Pre-Bottleneck stage of task 1 comprises: P1 = perception stage of task 1; Bottleneck stage of task 1 comprises: RS1 = response selection of task 1. Post-Bottleneck stage of task 1 comprises M1 = Motor stage of task 1; Pre-Bottleneck stage of task 2 comprises: P2 = perception stage of task 2; Bottleneck stage of task 2 comprise: RS2 = response selection stage of task 2; Post-Bottleneck stage of task 2 comprises: M2 = motor stage of task 2).

affecting task 1 processing with the start of the DT situation. To investigate whether participants perception of reward influences task 1 processing (even if reward is instructed for task 2), we tested for potential effects of reward on RT 1 and analyzed the potential net effect of such effects on RT 2 (Charron & Koechlin, 2010; Dambacher et al., 2011; Fischer et al., 2018; Hübner & Schlösser, 2010). For interpreting the latter we applied the effect propagation logic (Janczyk et al., 2019; Pashler & Johnston, 1989; Van Selst et al., 1999; Van Selst & Jolicoeur, 1997).

This logic predicts that processing manipulations in task 1 of an overlapping DT situation should propagate into the processing time of task 2 via the bottleneck if they occur at the combined time of the pre-bottleneck and/or bottleneck stages in task 1. This time would encompass the time interval from perception till the end of the response selection in task 1 (P1, RS1, see Fig. 2). Here, a factor that changes the processing time for the pre-bottleneck, and/or bottleneck stage in task 1 should also affect the processing time in task 2 at short SOA, when the response selection for task 2 has to wait until the response selection for task 1 has finished. Therefore, we should observe an *overradditive interaction* of SOA and reward on RT 2, if the perception of reward influences task 1 processing of the subjects. Fig. 2 illustrates the corresponding RT pattern: it shows that if reward decreases the duration of pre-bottleneck and/or bottleneck stages of task 1, then we should find shorter RT 2 in the rewarded versus the un-rewarded condition at short but not at long SOA. This is so because a reduced duration of pre-bottleneck and/or bottleneck stages of task 1 would result in an earlier onset of response selection for task 2 and, thus, shorter RT 2. At long SOA, however, no effect propagation from task 1 to task 2 should occur and no effects of reward on RT 2 should be observed. In that case, we should find an overadditive interaction of SOA and reward on RT 2 (Pashler & Johnston, 1989; Reimer et al., 2015; Schubert, 1999).

If, in contrast, reward would affect post-bottleneck stages in task 1, i.e. the motor stage of task 1, then we should not find any effect propagation from task 1 to task 2, neither for short nor for long SOA. As can be seen in Fig. 2b, this is so because reward would affect the processing stages of task 1 that occur after the response selection of task 1 has finished. Please, note, that in those cases (i.e. reward affects pre-bottleneck, bottleneck, or post-bottleneck stages) we should find a significant reduction of RT 1 in the rewarded compared to the un-rewarded condition. Importantly, however, additional loci of the reward effect during the execution of a DT situation are conceivable, one particular relevant case will be discussed in the general discussion section.

2. Experiment 1

In Experiment 1, we tested how the application of reward to task 2,

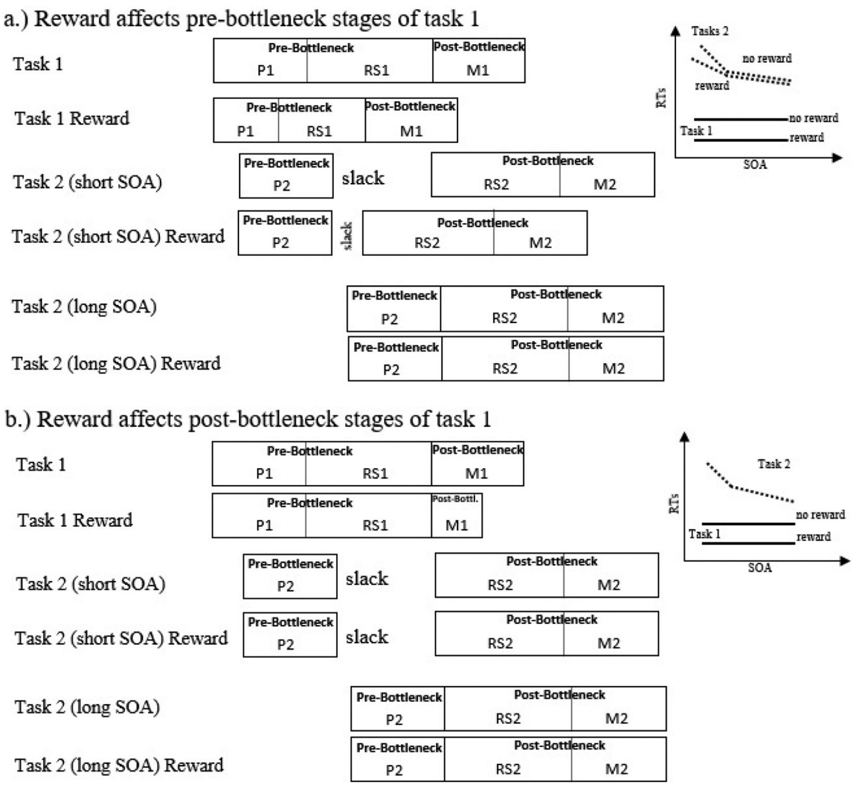

Fig. 2. Perceived reward influences processing of task 1 and RT predictions: a) Processing of task 1 and task 2, if participants perceived reward influences processing of the pre-bottleneck and/or bottleneck of task 1. Resulting in an overadditive interaction of reward and SOA on RTs. b) Processing of task 1 and task 2, if participants perceived reward influences processing of the post-bottleneck stage of task 1. Resulting in RT effects restricted to RT 1, not affecting RT 2. (Pre-Bottleneck stage of task 1 comprises: P1 = perception stage of task 1; Bottleneck stage of task 1 comprises: RS1 = response selection of task 1. Post-Bottleneck stage of task 1 comprises M1 = Motor stage of task 1; Pre-Bottleneck stage of task 2 comprises: P2 = perception stage of task 2; Bottleneck stage of task 2 comprises: RS2 = response selection stage of task 2; Post-Bottleneck stage of task 2 comprises: M2 = motor stage of task 2).

affected the perceived reward of the participants and its influence on task 1 and/or task 2 processing. In addition, we investigated whether reward affects pre-bottleneck, bottleneck, or post-bottleneck stages in DT situations. To tackle these questions we relied on the locus of slack and effect propagation logic (Janczyk et al., 2019; Pashler & Johnston, 1989; Reimer et al., 2015; Schubert, 1999; Schweickert, 1978; Van Selst et al., 1999; Van Selst & Jolicoeur, 1997). To this end, we applied an auditory-visual DT with three SOAs. Participants were instructed that they could earn a monetary reward if their response to task 2 was fast and accurate. Note that participants received their performance-contingent reward at the end of the experiment, therefore, it is the expectation of a potential reward and not the actual reception in a given trial that affects participants' performance. For the sake of brevity, we will refer to this expectancy of a reward simply as reward effect.

2.1. Material and methods

2.1.1. Participants

Eighteen healthy participants (10 male; *mean* (*m*) *age* = 26.5 years) took part in the experiment after obtaining written informed consent. We choose this particular sample size based on a priori power analyses conducted with the G*Power program of Faul, Erdfelder, Lang, and Buchner (2007). We conducted a power analysis for the main effect of reward (rewarded vs. un-rewarded) for Experiment 1. We added SOA (50 ms, 300 ms, 900 ms) for experiment 1 as a between-subjects factor because G*Power cannot be used for power analysis specifying the interaction of two within-subjects factors. Due to the lower power of between- compared with within-subjects designs this should result in an even more conservative estimate of the required sample size. For G*Power we defined the parameters (Faul et al., 2007) as follows: Test family: F tests; statistical test: ANOVA: Repeated measures, within factors; Type of power analysis: a priori; Effect size *f*: 0.6547 (which corresponds to an effect size of $\eta_p^2 = 0.30$; Based on Fischer et al., 2018), however using a more conservative estimate; α error prop: 0.05; Power (1-β error prob): 0.95; Numbers of groups 3; Number of measurements: 2; Corr. Among rep measure: 0.; Nonsphericity correction ε: 1. The calculated sample size amount to *N* = 18 for Experiment 1.[1] We note that our approach of calculating the estimated sample size leads in any case

[1] Please note, that according to an anonymous reviewer, it would also be possible to calculate the estimated sample size differently. In detail, conceptualizing the reward * SOA interaction as the main effect of SOA on the differences between reward and no reward scores. Additionally, the correlation among repeated measurements of 0 might be set at 0.5 resulting in an estimated sample size of *N* = 12 while applying otherwise identical settings in G*Power.

to sufficiently high enough power to assure the interpretations of the measured findings. Participants were paid 4 euros per hour for their participation. In addition, they could earn up to 4.32 euros due to the applied reward manipulation. The reward scheme will be discussed in detail below. The experimental protocol conformed to the declaration of Helsinki. All participants were right-handed, German native speakers, and had normal or corrected to normal vision. One participant had to be excluded due to error rates deviating more than two standard deviations (*SD*) from the mean of the other participants ($m = 48\%$).

2.1.2. Apparatus and stimuli

Participants performed a PRP-like DT consisting of an auditory and a visual choice RT task. Stimuli for the auditory task consisted of three sine-wave tones with a frequency of 250, 500, or 1000 Hz presented for 200 ms via headphones. Participants responded to the low-, middle-, and high-pitched tones by pressing the '<', 'Y', and 'X' keys of a QWERTZ keyboard with the ring, middle, and index fingers of their left hand, respectively. For the visual task, one of three digits (*1*, *5*, or *9*) was presented centrally on a computer screen with a visual angle of 52° x 0.31° at a viewing distance of 80 cm. Visual stimuli appeared for 200 ms and participants responded to the digits in ascending order by pressing the keys ',', '.', and '-' of a QWERTZ keyboard with the index, middle, and ring finger of their right hand. Participants were instructed to first respond to the auditory and then to the visual task.

Each trial started with the presentation of a fixation cross at the center of the screen for 1950 ms (see Fig. 3). The auditory stimulus was then presented for 200 ms. Subsequently, the visual stimulus was presented for 200 ms with an SOA of 100, 300, or 900 ms. After a response to both target stimuli or maximal response duration of 4500 ms, an intertrial interval (ITI) of 350 ms followed before the start of the next trial.

2.1.3. Design and procedure

A two-factor within-subjects design with SOA and reward as independent variables was used. Each block contained 27 trials resulting from the combination of 3 SOAs (100, 300, 900 ms), 3 auditory stimuli (250, 500, 1000 Hz), 3 visual stimuli (1, 5, 9). Reward was varied blockwise. In total, we applied 12 DT blocks, 6 with reward and 6 without. Overall, this resulted in 324 trials. The procedure was as follows: The experiment started with a single-task practice phase in which participants performed 12 single-task trials for each component task. The timing of these single-task trials was similar to DT trials with the exception that only one target stimulus was presented and only one response was required. These single-task trials were followed by 36 trials of DT practice. Subsequently, participants were instructed that, for rewarded blocks, they could earn 72 euro cent per block if their response to task 2 was fast and accurate. Participants' thresholds for earning a reward were calculated based on their mean RT 2 performance and their mean error rates in rewarded blocks and the mean RT 2 and mean error rates in a given rewarded block were compared to this threshold, to decide whether or not participants received a reward. For the first rewarded block, we set a pre-defined deadline of 1000 ms and 80% accuracy, based on a pilot study. If both, their mean RT 2 and mean error rate was below the pre-defined reference values, they received a reward. Thereafter, the reference RT was calculated by averaging the pre-defined deadline (1000 ms) and the mean RT 2 of the previous rewarded blocks. Similarly, the mean error rate was calculated. After every block, participants received feedback about their mean RT 2 and percentage of correct trials, for rewarded blocks, their earned reward. The order of the 8 rewarded and 8 un-rewarded blocks were randomized. Before each block, participants were informed, whether they could earn reward or not. Additionally, participants were naïve about the threshold computations for obtaining a reward.

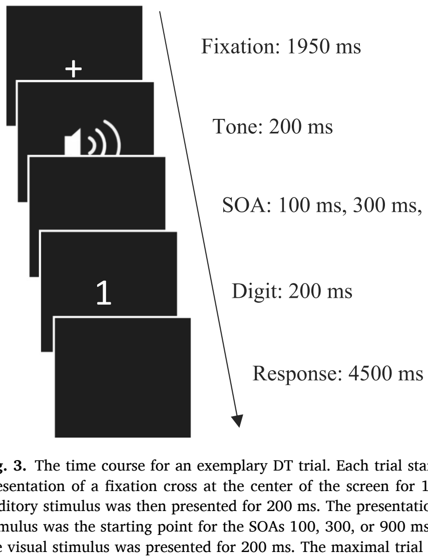

Fig. 3. The time course for an exemplary DT trial. Each trial started with the presentation of a fixation cross at the center of the screen for 1950 ms. The auditory stimulus was then presented for 200 ms. The presentation of the first stimulus was the starting point for the SOAs 100, 300, or 900 ms, after which the visual stimulus was presented for 200 ms. The maximal trial duration was set to 4500 ms. The intertrial interval (ITI) was 350 ms.

2.1.4. Statistical analysis

We analyzed mean RTs and error rates separately for RT 1 and RT 2 using an ANOVA with the within-subjects factors SOA and reward. A significance threshold of 5% was used for all analyses. The *p* values of the ANOVAs were adjusted according to the Greenhouse-Geisser correction when necessary. For the RT analyses, trials with at least one erroneous response ($m = 9\%$) and outliers that deviated more than $+/- 2.5$ SD for each participant and factor combination ($m = 2\%$) were excluded from the data set.

2.2. Results

2.2.1. Task 1

The first analysis tested the effects of reward on task 1 performance. We found a significant main effect of reward on RT 1, $F(1, 16) = 12.883$, $p < .002$, $\eta_p^2 = 0.446$. RT 1 was shorter in the rewarded condition ($m =$ 664 ms) compared with the un-rewarded condition ($m = 698$ ms; see

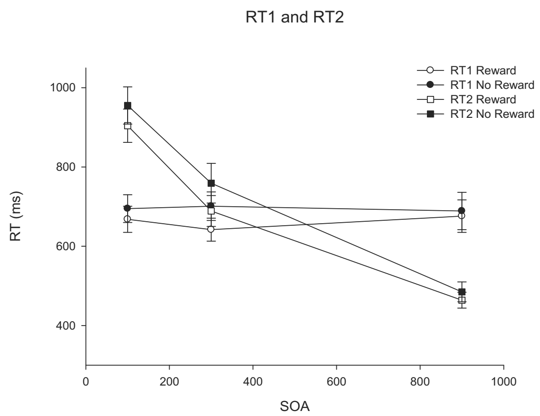

Fig. 4. Mean RT 1 and RT 2 as a function of SOA and reward for Experiment 1. Error bars represent the standard error of the mean.

Fig. 4). This main effect of reward on RT 1 indicates that the perceived reward influenced participants' processing of task 1 (although it was allotted by instruction to task 2). Furthermore, we found a significant interaction of reward × SOA, $F(1, 16) = 6.429$, $p < .004$, $\eta_p^2 = 0.287$ on RT 1.[2] The main effect of SOA, $F(2, 16) = 0.215$, $p = .691$, $\eta_p^2 = 0.013$, did not reach significance.

For the error rates in task 1, we found a significant main effect of SOA, $F(2,32) = 9.530$, $p < .001$, $\eta_p^2 = 0.373$. The error rates were higher for SOA 100 ($m = 7\%$) and the SOA 300 ($m = 7\%$) compared with SOA 900 ($m = 4\%$). Such effects of SOA on error rates for task 1 have often been explained by response grouping (Schubert, 1999; Ulrich & Miller, 2008). The effects of reward, $F(1, 16) = 1.636$, $p = .219$, $\eta_p^2 = 0.093$, and SOA × reward, $F(2, 32) = 0.174$, $p = .841$, $\eta_p^2 = 0.009$, did not reach significance.

2.2.2. Task 2

The second analysis tested the effects of reward on task 2 performance. We found a significant main effect of reward, $F(1, 16) = 14.325$, $p < .002$, $\eta_p^2 = 0.472$. As can be seen in Fig. 4, RT 2 was shorter in the rewarded condition ($m = 686$ ms) compared with the un-rewarded condition ($m = 733$ ms). Furthermore, we found a significant main effect of SOA, $F(2, 32) = 202.537$, $p < .001$, $\eta_p^2 = 0.927$. RT 2 increased from SOA 900 ($m = 475$ ms) to SOA 100 ($m = 925$ ms), indicating the typical PRP-effect (Pashler, 1994; Schubert, 1999).

Importantly, we found a significant overadditive interaction of the factors reward × SOA, $F(2, 32) = 7.236$, $p < .003$, $\eta_p^2 = 0.312$ on RT 2. Pairwise comparisons revealed a significantly larger difference between the reward effect at short ($m = 51$ ms) compared with long SOA ($m = 21$ ms), $t(16) = 2.246$, $p < .039$. This overadditive interaction of reward and SOA on RT 2 indicates that the reward effect on task 1 propagated into task 2. Importantly, according to the prediction outlined in the Introduction section, this pattern of results for RT 2 suggests that reward affects pre-bottleneck and/or bottleneck stages of task 1.

Additionally, we found a reward effect on task 2 performance at the longest SOA, $t(16) = 2.211$, $p < .042$, when comparing a rewarded to an unrewarded condition. Please note, that this pattern indicates an additional locus of the reward effect on task 2. We will discuss the implications in the general discussion section accordingly.

For the error rates in task 2, we found no significant main effects of the factors reward, $F(1, 16) = 0.435$, $p = .519$, $\eta_p^2 = 0.026$, SOA, $F(2, 32) = 1.775$, $p = .186$, $\eta_p^2 = 0.100$, nor of their interaction, $F(2, 32) = 0.565$, $p = .574$, $\eta_p^2 = 0.034$. All error rates for Experiment 1 can be found in Table 1.

Table 1
Mean rates of errors for task 1 and task 2 in % (and standard deviation) from Experiment 1 as a function of SOA and reward.

	Experiment 1			
	Reward			
	Reward		No reward	
SOA	Task 1	Task 2	Task 1	Task 2
100	14.16% (14.65%)	6.32% (7.14%)	18.30% (13.76%)	8.50% (10.46%)
300	8.48% (7.94%)	7.41% (10.14%)	11.78% (12.37%)	7.00% (11.70%)
900	7.20% (6.86%)	3.70% (5.24%)	9.80% (10.55%)	4.36% (5.89%)

2.3. Discussion

Experiment 1 revealed that participants' reward perception influenced task 1 processing, as indicated by the main effect of reward on RT 1 1. Furthermore, the reward effect propagated at short SOA from task 1 onto task 2, thus reducing RT 2. This conclusion is consistent with the observation of a larger reward effect on RT 2 at short compared to long SOA. Taken together, this data pattern confirms the model of perceived reward influencing pre-bottleneck and/or bottleneck stages of task 1.

An important precondition for this interpretation of the data of Experiment 1 is the assumption of a response selection bottleneck. Based on this presumption (and the data) we inferred that the reward effect is located at the pre-bottleneck and/or bottleneck stages of task 1 and that the reward effect was propagated from task 1 via the response selection bottleneck onto task 2, thus reducing RT 2. However, an alternative bottleneck model can also account for the findings of Experiment 1. More specifically, the ***response initiation bottleneck*** model assumes a bottleneck at the motor execution stage (De Jong, 1993; Karlin & Kestenbaum, 1968; Keele & Boies, 1973). Consequently, according to this model, perceived reward influencing the pre-bottleneck and/or bottleneck stages of task 1 would lead to a reduction of RT 1 and, at short SOA, to effect propagation onto task 2, thus reducing RT 2 in the rewarded compared to the un-rewarded condition. At long SOA we would expect no reward effects on RT 2 due to a lacking bottleneck between task 1 and task 2. This could in turn explain the observed overadditive interaction of reward and SOA on RT 2 in Experiment 1. However, under the alternative precondition, that the locus of the bottleneck is located at the response initiation stage, this would imply that the reward effect was NOT propagated from task 1 onto the task 2 response selection stage but directly onto the motor stage in task 2. Therefore, in Experiment 2, we tested whether the reward effect propagated from task 1 via the response selection bottleneck onto task 2, or whether the reward effect propagated from task 1 via the motor stages onto task 2 as had been the case, if a response initiation bottleneck had been operating between the two tasks.

3. Experiment 2

In Experiment 2, we added a difficulty manipulation of the response selection of task 2, by applying a compatible (easy) versus an incompatible response-to-stimulus assignment (hard) and analyzed the effects of this manipulation in addition to that of SOA and of reward by applying the locus of slack and the effect propagation logic. Specifically, the difficulty manipulation in combination with the SOA manipulation allows us to infer whether a response selection bottleneck or a response initiation bottleneck had been operating while participants performed the current DT situation (Johnston & McCann, 2006; McCann & Johnston, 1992; Pashler & Johnston, 1989; Schubert, 1999; Schubert et al., 2008). For that purpose, we have to consider the predictions of the locus of slack logic concerning the effects of difficulty and SOA on RT 2 in more detail. The effects of reward will be regarded separately, below.

First of all, let's consider a situation in which a response selection bottleneck was interrupting the task 2 processing chain. In that case, we should observe an increase of the time for the response selection in the hard compared to the easy condition of task 2 on the RT 2. As can be seen in Fig. 5, this should lead to additive effects of SOA and response selection difficulty on RT 2. The RT 2 in the hard condition should be prolonged for about the same amount of time at short and long SOA because the additional amount of time for the response selection will be added to RT 2 after the bottleneck interruption in task 2. In addition to this additive effect pattern of SOA and difficulty on RT 2, we expected to replicate the findings from Experiment 1, that participants' perceived reward influences task 1 processing and that the resulting reward effect

[2] There is evidence that task order scheduling costs arise particularly at short SOA, reward could lead to a facilitation at shorter SOA compared to longer SOA, in the rewarded compared to the unrewarded condition. Thus producing the observed increased reward effects for shorter compared to longer SOAs as reflected by the interaction of SOA × reward on RT 1 (De Jong, 1995; Kübler et al., 2018).

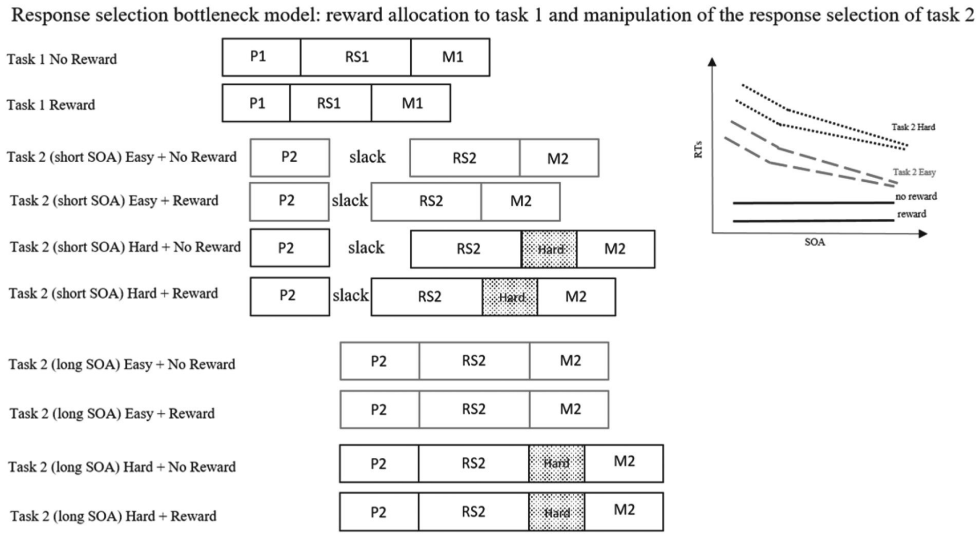

Fig. 5. Response selection bottleneck model including participants perceived reward influencing the processing of task 1 and difficulty manipulation of the response selection of task 2 and RT predictions: Additive effects of the difficulty manipulation and SOA on RTs should emerge, if the response selection stages of both tasks are processed serially, favoring the response selection bottleneck model (Easy = rule-based stimulus-response mapping (in red color); Hard = arbitrary stimulus-response mapping; P1 = perception stage of task 1; RS1 = response selection stage of task 1; M1 = Motor stage of task 1; P2 = perception stage of task 2; RS2 = response selection stage of task 2; M2 = motor stage of task 2.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

is propagated onto task 2 at short SOA. As can be seen in Fig. 5, this would lead to an overadditive effect pattern of SOA and reward on task 2, which we should observe in addition to the mentioned additive effects of SOA and difficulty on RT 2.

What should be expected in a situation in which a response initiation bottleneck had interrupted the processing chain of task 2? In that case, we should observe an underadditive interaction of SOA and response selection difficulty on RT 2. As illustrated in Fig. 6, the increase of the processing time for the hard compared to the easy difficulty response selection condition would be absorbed into slack at short SOA but not at long SOA. At long SOA we should observe longer RT 2 in the hard compared to the easy difficulty condition and as result, we should observe smaller difficulty effects on RT 2 at short compared to long SOA. Again, RT 2 and RT 1 would, additionally, be modulated by the reward effect, which should lead to a decrease of RT 1 in the rewarded compared to the un-rewarded condition and which should lead to an overadditive effect pattern at RT 2 because of the effect propagation from task 1 onto task 2 (please, refer to Fig. 6).

3.1. Material and methods

3.1.1. Participants

Twenty-eight healthy participants (21 female; *mean* (*m*) *age* = 22.5 years, *SD* = 3.0 years) were invited to take part in the experiment after obtaining written informed consent. We choose this particular sample size based on a priori power analyses conducted with the G*Power program of Faul et al. (2007). We conducted a power analysis for the main effect of reward (rewarded vs. un-rewarded) for Experiment 2. The parameters were identical to Experiment 1 (see method section). Resulting in a sample size of $N = 20$. However, we increased the sample size due to the larger difficulty of Experiment 2. Participants were paid 4 euros per hour for their participation. In addition, they could earn up to 5.67 euros due to the applied reward manipulation. The reward scheme will be discussed in detail below. The experimental protocol conformed to the declaration of Helsinki. All participants were right-handed, German native speakers, and had normal or corrected to normal vision. Three participants had to be excluded due to technical issues.

3.1.2. Apparatus and stimuli

The apparatus and the stimuli were the same as in Experiment 1. For the easy condition, we employed the same stimulus-response mapping as in Experiment 1. For the hard condition, we used an arbitrary (rather than a compatible) stimulus-response mapping for the visual task (task 2). In this condition, participants responded to the digits 1, 5, and 9 by pressing the '.', '-', and ',' button of a QWERTZ keyboard with the index, middle, and ring finger of their right hand. The trial sequence was identical to Experiment 1 with the exception that we included an additional SOA of 50 ms. We aimed at investigating in more detail the time course of RT 2 over the temporal overlap of both tasks.

3.1.3. Design and procedure

A three-factor within-subjects design with SOA and reward and compatibility as independent variables were used. Each block consisted of 36 trials resulting from the combination of 4 SOAs (50, 150, 300, 900 ms), 3 auditory stimuli (250, 500, 1000 Hz), 3 visual stimuli (1, 5, 9). Reward was varied blockwise. In total there were 16 blocks, 8 with reward and 8 without, which resulted in overall 576 trials. The procedure was analogous to Experiment 1. After 24 single-task practice trials (12 for each component task) participants performed 36 trials of DT practice. Subsequently, participants were instructed that, for rewarded blocks, they could earn 72 euro cent per block if their response to task 2 was fast and accurate. Like in Experiment 1, participants' thresholds for earning a reward were calculated based on their mean RT 2 performance and their mean error rates in rewarded blocks, and the mean RT 2 and mean error rates in a given rewarded block were compared to this threshold, to decide whether or not participants received a reward. For the first rewarded block, we set a pre-defined deadline of 1000 ms and 80% accuracy, based on a pilot study. If

L.E. Langsdorf et al. Acta Psychologica 222 (2022) 103465

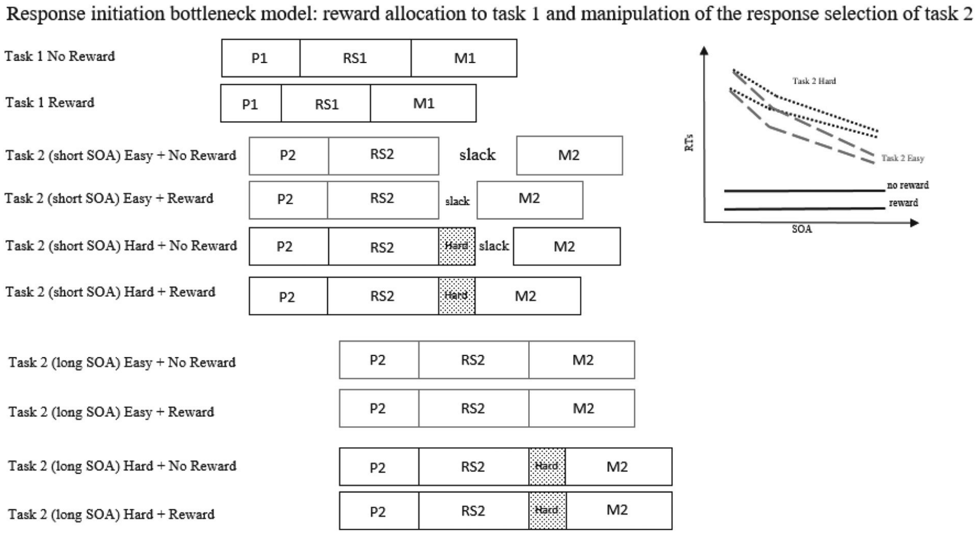

Fig. 6. Response initiation bottleneck model including participants perceived reward influencing the processing of task 1 and difficulty manipulation of the response selection of task 2 and RT predictions: Underadditive effects of the difficulty manipulation and SOA on RTs should emerge if the response selection stages of both tasks are processed concurrently, favoring the response initiation bottleneck model (Easy = rule-based stimulus-response mapping (in red color); Hard = arbitrary stimulus-response mapping; P1 = perception stage of task 1; RS1 = response selection stage of task 1; M1 = Motor stage of task 1; P2 = perception stage of task 2; RS2 = response selection stage of task 2; M2 = motor stage of task 2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

both, their mean RT 2 and mean error rate was below the pre-defined reference values, they received a reward. Thereafter, the reference RT was calculated by averaging the pre-defined deadline (1000 ms) and the mean RT 2 of the previous rewarded blocks. Similarly, the mean error rate was calculated. After every block, participants received feedback about their mean RT 2 and percentage of correct trials, for rewarded blocks, their earned reward. The order of the 8 rewarded and 8 unrewarded blocks were randomized. Before each block, participants were informed, whether they could earn reward or not. Additionally, participants were naïve about the threshold computations for obtaining a reward.

3.1.4. Statistical analysis

We analyzed mean RTs and error rates separately for RT 1 and RT 2 using an ANOVA with the within-subjects factors SOA, reward, and task 2 difficulty. A significance threshold of 5% was used for all analyses. The p values of the ANOVAs were adjusted according to the Greenhouse-Geisser correction when necessary. For the RT analyses, trials with at least one erroneous response ($m = 11\%$) and outliers that deviated more than +/− 2.5 SD ($m = 2\%$) were excluded from the data set.

3.2. Results

3.2.1. Task 1

Similar to Experiment 1, in Experiment 2 we found a significant main effect of reward on RT 1, $F(1, 27) = 33.808$, $p < .002$, $\eta_p^2 = 0.556$. RT 1 was shorter in the rewarded (m = 725 ms) compared with the unrewarded condition (m = 778 ms), again indicating perceived reward influenced task 1 processing (see Fig. 7). Furthermore, we found a significant main effect of the factor compatibility on RT 1, $F(1, 27) = 11.930$, $p < .001$, $\eta_p^2 = 0.306$, indicating shorter response times in the easy (m = 737 ms) than in the hard condition (m = 767 ms). In addition, we found a significant main effect of SOA on RT 1, $F(3, 27) = 20.293$, $p < .001$, $\eta_p^2 = 0.429$. Such effects of SOA on task 1 are often explained by participants' tendency for response grouping (Schubert, 1999; Strobach, Schütz, & Schubert, 2015; Ulrich & Miller, 2008). Also, we found a significant interaction of compatibility × SOA, $F(3, 81) = 5.629$, $p < .001$, $\eta_p^2 = 0.173$. Neither the interaction of reward × compatibility, $F(3, 81) = 1.106$, $p = .302$, $\eta_p^2 = 0.039$, the interaction of reward × SOA, $F(3, 81) = 0.927$, $p = .431$, $\eta_p^2 = 0.033$, nor the three-way interaction of reward × compatibility × SOA, $F(3, 81) = 1.236$, $p = .302$, $\eta_p^2 = 0.044$, reached significance. Overall, similar to Experiment 1, we again found evidence for perceived reward influencing task 1 processing as indicated by the main effect of the factor reward on RT 1 (Fig. 7).

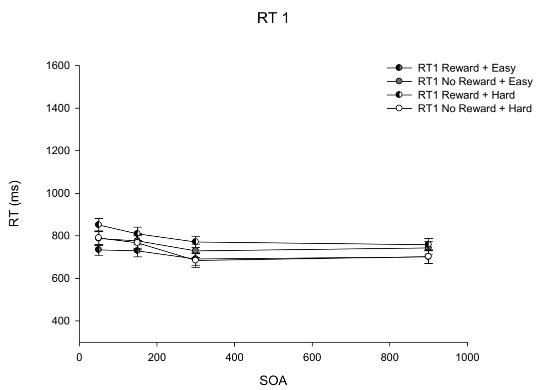

Fig. 7. Mean RT 1 for task 1 as a function of SOA, reward, and compatibility for Experiment 2. Error bars represent the standard error of the mean.

For the error rates in task 1, the only significant factor was SOA, $F(3, 27) = 4.955$, $p < .003$, $\eta_p^2 = 0.155$. No other effect or interaction was significant (all $ps < 0.217$).

3.2.2. Task 2

We found a significant main effect of SOA, $F(3, 27) = 503.625$, $p < .001$, $\eta_p^2 = 0.949$. RTs increased from long SOA ($m = 592$ ms) to short SOA ($m = 1139$ ms), $t(27) = 31.236$, $p < .001$, indicating a typical PRP-effect. Similarly to Experiment 1, we found a significant main effect of reward on RT 2, $F(1, 27) = 38.897$, $p < .001$, $\eta_p^2 = 0.590$. RT 2 was reduced in the rewarded condition ($m = 864$ ms) compared with the un-rewarded condition ($m = 931$ ms). This main effect was further specified by the reward × SOA interaction, $F(3, 81) = 4.698$, $p < .004$, $\eta_p^2 = 0.148$. Pairwise comparisons revealed a larger reward effect on task 2 at the shortest ($m = 87$ ms) compared with longest SOA ($m = 37$ ms), $t(27) = 3.940$, $p < .001$, indicating a propagation of the reward effect from task 1 to task 2, and leading to an overadditive interaction of reward and SOA on RT 2 (Fig. 8). Additionally, as in Experiment 1, we found a reward effect on task 2 performance at the longest SOA, $t(27) = -4.237$, $p < .001$, when comparing a rewarded to an unrewarded condition. Please note, that this pattern indicates an additional locus of the reward effect on task 2. We will discuss the implications in the general discussion section accordingly.

Furthermore, we observed a significant main effect of the factor compatibility, $F(1, 27) = 98.130$, $p < .001$, $\eta_p^2 = 0.784$. RT 2 was shorter in the easy condition ($m = 804$ ms) compared with the hard condition ($m = 991$ ms). Importantly, we found no significant effect for the compatibility × SOA interaction, $F(3, 81) = 1.332$, $p = .270$, $\eta_p^2 = 0.047$. This finding is not consistent with the assumption of a bottleneck at the response initiation initiation stage. Instead, it points to serial processing of the response selection stages and to a response selection bottleneck. Interestingly, we found a significant interaction of the factors reward × compatibility, $F(3, 81) = 6.269$, $p < .019$, $\eta_p^2 = 0.188$. Pairwise comparisons revealed a larger reward effect in the hard condition ($m = 88$ ms) compared to the easy condition ($m = 46$ ms), $t(27) = 2.504$, $p < .019$. This finding indicates, that increased response selection difficulty may lead to stronger reward effects, which will be further discussed in the general discussion (Botvinick & Braver, 2015; Brehm & Self, 1989). The three-way interaction of reward × compatibility × SOA, $F(3, 81) = 1.822$, $p = .150$, $\eta_p^2 = 0.063$, did not reach significance.

For the error rates in task 2, we found a significant main effect for compatibility, $F(3, 27) = 6.206$, $p < .019$, $\eta_p^2 = 0.187$, and a significant interaction of compatibility and SOA, $F(3, 81) = 4.279$, $p < .013$, $\eta_p^2 = 0.137$. No other effect or interaction was significant (all $ps < 0.122$). All error rates for Experiment 2 can be found in Table 2.

3.3. Discussion

In Experiment 2, we replicated the main finding of Experiment 1. As indicated by the main effect of reward on RT 1 and the significant overadditive interaction of reward and SOA on RT 2, reward influenced again task 1 processing and propagated onto task 2. The effect propagation via the bottleneck took place at short SOA but not (or to a lesser extent) at long SOA, which caused that the reward effect on RT 2 was larger at short compared to long SOA. As an additional question, we asked whether the reward effect was propagated via the bottleneck from task 1 onto the response selection or onto the motor stage of task 2. Note that the former location of the effect propagation would be predicted if a response selection bottleneck had been operating between both tasks, while the latter would be consistent with the assumption of a response initiation bottleneck operating in the current DT situation.

For that purpose, we increased the response selection difficulty in task 2 and analyzed its effects and that of SOA on the RT 2 using the locus-of-slack logic (Schubert, 1999; Schweickert, 1978). Importantly, we found an effect of the response selection difficulty on task 2 at short SOA. This finding is not consistent with the assumption of a response initiation bottleneck model since this model would predict absorption of the additional time for the hard compared with the easy condition into the slack time at short SOA and, thus, an underadditive SOA × difficulty interaction on RT 2. Instead, our findings are in line with the assumptions of the response selection bottleneck model because they suggest additive effects of response selection difficulty and SOA on RT 2. Consequently, the findings of Experiment 2 extend our previous findings and indicate that the reward effect on task 1 is propagated onto the response selection stage of task 2.

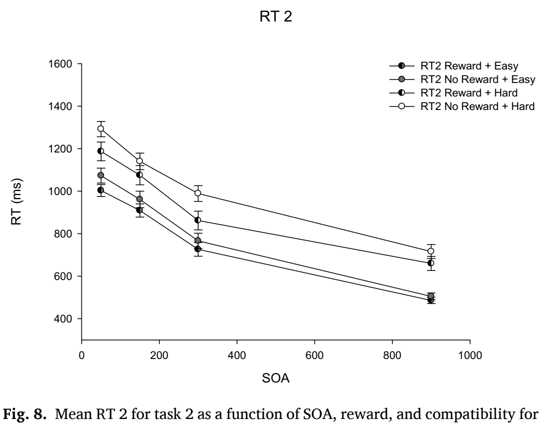

Fig. 8. Mean RT 2 for task 2 as a function of SOA, reward, and compatibility for Experiment 2. Error bars represent the standard error of the mean.

4. General discussion

The present study investigated the influence of reward on DT performance. More specifically, we investigated how participants' perception of reward influenced task processing in a DT situation. For this purpose, we applied reward to task 2 and tested whether participants' task 1 and/or task 2 processing were influenced. In addition, we also investigated which processing stage of the tasks is affected by the reward application. For this purpose, in Experiment 1, we employed the locus of slack and the effect propagation logics. The results indicate that perceived reward influences participants processing of task 1 – even when, by instruction, reward was assigned to task 2. This was reflected by reduced RT 1 in the rewarded compared with the un-rewarded condition. Furthermore, we demonstrated that the reward effect from task 1 propagated onto task 2 as indicated by the overadditive interaction of reward and SOA on RT 2. In Experiment 2, we replicated these results and provided evidence for the assumption that the reward effect is propagated via the bottleneck from task 1 onto the response selection rather than the motor stage of task 2. To this end, we added a difficulty manipulation of the response selection stage of task 2. Together with the locus of slack logic, this approach enabled us to explicitly test for the locus of the effect propagation onto task 2. Importantly, the observed data pattern contradicts the assumptions of the response initiation bottleneck model which assumes an effect propagation via the bottleneck onto the motor stage of task 2. Instead, our data favor the assumptions of the response selection bottleneck model which presumes a propagation of the reward effect via the bottleneck onto the response selection stage of task 2.

4.1. Perceived reward effects in dual-task situations

Previous studies have already provided evidence for a reward-related improvement of DT performance (Fischer et al., 2018; Han & Marois, 2013; Yildiz et al., 2013). So far, however, the precise mechanisms underlying the reward effect in DT situations have not been investigated. Concerning this issue, so far, it still remained open how participants perceived reward influences DT processing. In the current study, we provided reward for task 2 performance. Consequently, the participant's perceived reward could influence task 2 processing as

Table 2
Mean rates of errors for task 1 and task 2 in % (and standard deviation) from Experiment 2 as a function of SOA, reward and, compatibility.

	Experiment 2							
	Compatibility - reward							
	Easy - reward		Easy – no reward		Hard - reward		Hard - no reward	
SOA	Task 1	Task 2	Task 1	Task 2	Task 1	Task 2	Task 1	Task 2
50	4.86% (7.11%)	3.27% (4.35%)	5.56% (7.39%)	2.89% (5.58%)	4.66% (7.41%)	8.23% (13.60%)	3.78% (5.08%)	8.83% (13.84%)
150	4.37% (7.27%)	2.18% (5.26%)	4.46% (6.16%)	2.98% (6.50%)	3.67% (6.37%)	7.04% (12.22%)	3.47% (5.11%)	8.23% (13.13%)
300	2.28% (4.96%)	2.08% (3.67%)	3.67% (6.80%)	4.27% (6.16%)	3.07% (5.09%)	6.75% (12.77%)	2.48% (3.81%)	8.61% (13.70%)
900	4.07% (6.02%)	1.79% (3.31%)	4.27% (8.02%)	2.38% (5.28%)	3.97% (5.15%)	9.92% (13.17%)	2.68% (4.75%)	9.72% (13.36%)

instructed, or alternatively task 1 processing or both. Importantly, we could show that participants perceived reward influenced task 1 processing, as indicated by reduced RT 1 in the rewarded compared with the un-rewarded condition. In addition, this reward effect, propagated onto task 2, as was indicated by larger reward effects on RT 2 at short compared with long SOA. This is a novel and important finding, since, for the first time, we could show how participants perceived reward influenced task processing in a DT situation.

However, the question arises why was participants task 1 processing influenced by reward – despite the instructional application of reward to task 2? The answer could be related to how participants represent DT situations. From recent studies, there is now ample evidence that, rather than representing DTs as two distinct and serially executed tasks, participants represent DT situations as a whole combined task. Several studies suggest that both component task representations are integrated into a higher-order representation representing the entire DT (Hirsch et al., 2017; Kübler et al., 2018; Kübler et al., 2019; Kübler et al., 2021; Schubert & Strobach, 2018; Strobach et al., 2014a). Consequently, reward cannot be allocated selectively to task 2, but instead, reward is allocated to the DT representation comprising the entire DT situation. As a result, we found reward effects already for task 1. Alternatively, it might also be the case that the distinct representations of task 1 and task 2 are not separately and independently accessible for participants. Evidence for this assumption stems from studies investigating the introspective awareness of capacity limitations in DT situations. These studies showed that participants are not able to reliably report their produced DT costs in task 2 in a DT situation. This could further indicate that a specific reward assignment to task 2 is not possible, because participants lack independent and conscious access to task 2 (Bryce & Bratzke, 2014; Marti, Sackur, Sigman, & Dehaene, 2010). Further support for the integrated DT processing hypothesis comes from DT studies relying on the investigation of partial repetition costs an index derived from the feature binding of action control approach (Hommel, 1998, 2020). In particular, assuming that participants store both tasks of a DT situation in one single memory episode, that is retrieved whenever one of the task components (stimulus or response) of either task is repeated from trial n-1 to trial n. In case of a full repetition, i.e. when both stimuli are repeated, thus producing an identical memory trace from trial n-1 to trial n, this can lead to a reduction of RTs, while a partial repetition can result in a prolongation of RTs compared to the full repetition conditions or full switch conditions (no repetition between trial n-1 and trial n). The results suggest that participants do not separate the task processing of both tasks, but process both tasks in an integrated fashion, as indicated by partial repetition costs (Pelzer, Naefgen, Gaschler, & Haider, 2021). Future studies might specify whether or not the degree of task integration across these different operationalizations of task integration (i.e. higher task order representation, introspective awareness, binding effects across component tasks) can be modulated by the application of reward. It would be of special interest whether or not the separate administration of reward to task 1 or to task 2 can affect the degree to which the two tasks of the dual-task situation will be processed in an integrated fashion.

As previously mentioned, it cannot be ruled out that reward affected the processing stages of task 2 *in addition* to the observed effect on the pre-bottleneck and/or bottleneck stages of task 1. In detail, a reward effect at the longest SOA indicates that it cannot be accounted for completely, with effect propagation. That is the case because a reward effect can only be propagated if both tasks overlap in time. Since that is not the case during the longest SOA an observed reward effect on task 2 performance indicates an additional source of reward effect during the execution of task 2. Importantly, this additional reward effect during the processing of task 2 cannot be explained with reward affecting only the post-bottleneck stages of task 2, if that was the case we would predict an additive effect of reward and SOA on RT 2. It is conceivable that due to the increased SOA, participants' time to prepare for the upcoming task 2 led to an improvement especially in the rewarded compared to the unrewarded condition, as task preparation processes seem to be initiated earlier in rewarded compared to unrewarded conditions (Schevernels, Krebs, Santens, Woldorff, & Boehler, 2014). Alternatively, it is possible that the task instruction that especially task 2 performance will be rewarded, contributed to the observed finding of a reward effect on task 2 performance at long SOA. In particular, participants might have processed task 2 at long SOA in a more isolated fashion than at short SOA. Therefore at long SOA, the instruction that task 2 performance will be rewarded, might have resulted in a pure reward effect to task 2 performance. To clarify how reward affects DT performance, and how task instructions are related to that, further research is required in which task 1 performance would be rewarded and the corresponding effects on RTs in task 1 and task 2 would be analyzed.

4.2. *Localization of the reward effect*

In the current study, we investigated whether pre-bottleneck, bottleneck, or post-bottleneck stages were affected by the application of reward. The main effect of reward on RT 1 and the greater reward effects at short compared to long SOA on RT 2 indicate that pre-bottleneck and/or bottleneck stages, i.e. either the perceptual and/or the response selection stages of task 1 were affected by the application of reward.

Importantly, as indicated in the introduction section of the locus of slack technique, a multitude of different loci of the reward effect is quantifiable with this particular approach, however, a specific combination of loci of the reward effect on task 1 is of special interest for the case at hand. In detail, reward may have affected the motor stage of task 1 *in addition*[3] to the observed reward effects on pre-and/or bottleneck stages. That could be the case because the additional effect on the motor stage of task 1 would not be propagated onto task 2 (because the reward effect would occur after the response selection stage of task 1). And since we observed a main effect of reward on task 1 performance, we would not be able to distinguish whether or not the motor stage of task 1 was affected *in addition*. In particular, if there is an *additional* locus of the reward effect on the motor stage of task 1, we should observe a greater

[3] We thank an anonymous reviewer for pointing out that theoretically and empirically relevant scenario.

net reward effect on task 1 compared to task 2. That is so because some residual reward effect is *not propagated* from task 1 onto the response selection stage of task 2 (see the main finding of experiment 2) affecting the motor stage of task 1. However, a closer examination of the data indicates the opposite. In detail, for Experiment 1, we observed an increased reward effect on task 2 at short SOA compared to task 1 ($p <$ .05). Furthermore, we observed descriptive differences between the reward effect on task 1 ($m = 34$ ms) and task 2 ($m = 47$ ms) indicating greater reward effects on task 2. A similar data pattern emerges for Experiment 2, in particular, the reward effect on task 2 at short SOA increased compared to task 1 ($p < .01$). As in Experiment 1, we observed descriptive differences between the reward effect on task 1 ($m = 53$ *ms*) and task 2 ($m = 67$ ms) indicating greater reward effects on task 2, which would be opposite to the assumption that there was a reward effect on the motor stage in addition to the effect on the pre-bottleneck and/or bottleneck stages of task 1. In sum, the locus of slack technique enables a variable, as well as a precise analysis of reward processing in DT situations, indicating that that the application of reward affected pre-bottleneck and/or bottleneck stages of task 1.

This finding is further supported by evidence that reward improves the performance in paradigms related to attentional and/or perceptual processes such as spatial cueing, negative priming, and the Erikson flanker task (Dambacher et al., 2011; Engelmann et al., 2009; Engelmann & Pessoa, 2007; Engelmann & Pessoa, 2014; Hübner & Schlösser, 2010; Kiss et al., 2009). Extending these previous findings to DT situations, it is conceivable that the application of reward leads to a reduction of the perceptual stage due to increased perceptual sensitivity. Consequently, the perception of the stimulus is conducted faster and the subsequent stages can start earlier reducing RTs (Engelmann et al., 2009; Engelmann & Pessoa, 2014; Padmala & Pessoa, 2010, 2011; Pessoa & Engelmann, 2010). However, there have also been hints that the response selection stage might be affected by the application of reward (Etzel, Cole, Zacks, Kay, & Braver, 2016; Kennerley & Wallis, 2009). According to this account, it might be that reward modulates the updating and the maintenance of task-relevant information in working memory. This could lead to a shortening of the response selection stage and, thus, an earlier initiation of subsequent stages. As a third explanation, It might be that reward modulates additional control processes required for the efficient execution of DT situations. There are theoretical approaches that extend the classical bottleneck assumption by assuming further cognitive control processes. These control processes are necessary for relevant task information to be maintained, coordinated, and updated within working memory (Etzel et al., 2016; Kennerley & Wallis, 2009; Kübler et al., 2018; Kübler et al., 2019; Kübler et al., 2021; Schubert & Strobach, 2018). These control processes must be executed before the tasks are performed. If reward leads to a shortening of these control processes, the relevant task processes could start earlier and, thus, result in a shortening RTs for both tasks.

The latter view is also in line with recent neuromodulatory accounts that propose a connection between reward, cognitive control, the dopamine system located in the midbrain, and the lateral prefrontal cortex (lPFC). Specifically, phasic dopamine signals from PFC are discussed to be involved in the “gating” of afferent input to lPFC marking the relevant task-related information thus enabling updating and maintenance of the relevant information (Braver & Cohen, 2000; Durstewitz & Seamans, 2008; Etzel et al., 2016; Kennerley & Wallis, 2009; Shen & Chun, 2011). Together with recent evidence that dopaminergic neurons respond with phasic firing to predictive reward cues (Bayer & Glimcher, 2005) the reasoning laid out by Etzel et al. (2016) might be also applicable here. According to this account, the prospect of reward serves as a cue triggering phasic dopamine responses. The dopamine response, in turn, can modulate task set afferent signals to the lPFC, leading to enhanced activation of task representation in the lateral prefrontal cortex, as well as their succeeding active maintenance within the frontoparietal cognitive control network. It could be that task-relevant goals, such as obtaining a reward, are connected to the representation of information by modulating executive functions such as updating and more generally the access to working memory (Kennerley & Wallis, 2009).

A further important aspect is what constitutes room for reward-related improvement.[4] In particular, one possible assumption might be that the performance of participants fluctuates across trials stronger in the unrewarded compared to the rewarded condition. This assumption was investigated by analyzing the SDs of RT 1 and RT 2 for both experiments, as an indicator of fluctuation of task performance in rewarded compared to unrewarded conditions. The analysis confirmed the idea that in rewarded in contrast to unrewarded conditions task 1 and task 2 performance fluctuated less. This may indicate, that participants exerted more cognitive control over a sustained period in the rewarded compared to the unrewarded condition (Braver, 2012; Locke & Braver, 2008). The results further indicate that the application of reward had a general effect on dual-task performance reducing RTs, however additionally encouraging participants to try hard enough thereby reducing the fluctuations in the participant's attention levels.

4.3. The locus of effect propagation on task 2

A further aim of Experiment 2 was to elucidate how (i.e. at which locations in the processing chain) the reward effect is propagated from task 1 onto task 2. The combination of the manipulation of the response selection stage of task 2 and the locus of slack logic has been used in a plethora of studies to test for whether or not certain processing manipulations occur before, at, or beyond a bottleneck within the processing chain of PRP task (e.g., Johnston & McCann, 2006; McCann & Johnston, 1992; Reimer et al., 2015; Schubert, 1999; Schubert et al., 2008). So far, however, this approach has not been used to investigate the locus of the reward effect and the locus of effect propagation in DT situations. The current results show that, the reward effect was propagated from task 1 onto the response selection stage of task 2 and that the response selection processes in the two tasks had been processed serially in the current task situation, thus constituting a central bottleneck. There is a further interesting implication to the confirmation of a bottleneck at the response selection stage. This implication relates to an assumption formulated by Meyer and Kieras (1997) according to which the serial processing of response selection in PRP tasks results from strategic deferment of the response selection in task 2. According to Meyer and Kieras (1997), motivation applied in the form of reward should be regarded as an important factor, which might counteract such a strategic deferment of task 2 processing and which, consequently, would cause overcoming of serial scheduling of the response selection stages. In the theory of Meyer and Kieras (1997), this would lead to a more concurrent processing of the central response selection stages. Importantly, the findings from Experiment 2 provide no empirical evidence for the assumption that reward does lead to a strategically evoked concurrent processing mode at the response selection stage. Instead, the data provided in this study favor the response selection bottleneck model and thus the serial processing of the response selection stages of both tasks. Therefore, our findings indicate that the central bottleneck processing (being it caused either by structural or strategic reasons) persists even if reward is applied to task 2. Nevertheless, it remains open to other

[4] We thank one anonymous reviewer for pointing this out. Following the data for the analysis of the SD of RT 1 and RT 2 comparing a rewarded to an unrewarded condition across both experiments as an indicator of the fluctuation of participants performance. In particular, for Experiment 1 we observed significant difference in the SD of RT 1, $t(15) = 3.74$, $p < .01$ as well as for the SD of RT 2, $t(15) = 3.06$, $p < .01$. For Experiment 2, a similar pattern was observed. For the SD of RT 1, $t(26) = 1.97$, $p < .05$ as well as for the SD of RT 2, $t(26) = 3.65$, $p < .05$, a significant difference was measured (Kirk, 1990). The results clearly indicate across both experiments that participants performance fluctuated less in rewarded compared to unrewarded conditions.

studies whether or not the usually observed serial processing between the response selection processes in PRP task situation is subject to structural or strategically determined serial processing (see e.g. Pashler, 1994; Schubert, 1999; or for other accounts Meyer & Kieras, 1997; Salvucci & Taatgen, 2008). While this variety of theoretical frameworks represents a vivid discussion in the field of dual-tasking research, it was beyond the scope of this study to clarify the precise mechanisms that lead to performance decrements (see for a different model approach Tombu & Jolicœur, 2003), in multi-tasking situations. The specific aim of the current study was to investigate *reward processing* in dual-tasking situations and the findings showed that the application of the locus-of-slack logic allows for important inferences about the mechanisms of how reward affects performance in an overlapping DT situation.

Interestingly in Experiment 2, we found stronger reward effects in the hard compared to the easy condition. This is in line with motivational theories connecting the increase in task difficulty with an increase in motivation (Botvinick & Braver, 2015; Brehm & Self, 1989; Gendolla & Richter, 2010; Kool, Shenhav, & Botvinick, 2017). Consequently, participants in the hard condition were additionally motivated thus producing stronger reward effects compared to the easy condition.

5. Conclusion

To conclude, the present study provides insights into the mechanism underlying the effect of reward in DT situations. We could show that participants perceived reward influenced pre-bottleneck stages of task 1 and that the effect of reward propagated onto the response selection stage of task 2. Together, these findings constitute first insights into participants' perceived reward processing in DT situations.

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Ethical approval

All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Consent to participate

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

Consent for publication

All participants gave their informed consent to use their data for publication.

Availability of data and material

The material used and the datasets generated and analyzed during the current study are available from the corresponding author on request.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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On the temporal dynamics of reward utilization in dual-task situations

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Abstract

In dual-task (DT) situations, performance typically deteriorates compared with single-tasking situations. These decrements can be explained by the serial scheduling of response selection stages constituting a central bottleneck as with decreasing stimulus-onset asynchrony (SOA) the reaction time for the second task (Task 2; RT2) increases. Prior studies indicated that the reaction time for the first task (Task 1; RT1) and RT2 are improved in reward compared with no-reward conditions for a block-wise reward prospect, which reflects reward-related optimization in DT processing. However, it remains unclear whether participants can flexibly utilize reward information in a trial-by-trial manner to achieve reward-related improvements. Additionally, it is unclear whether a potential reward-related optimization reflects optimized task preparation only or whether the prospect of reward can evoke an *additional* task optimization mechanism that extends beyond preparation-related processing improvements. For Experiment 1, we combined a trial-wise reward prospect for participants' Task 1 performance, which was signaled by a cue before Task 1 onset, with block-wise presented cue–target intervals (CTI) of either 200 ms *or* 700 ms, resulting in precise temporal predictability of Task 1 onset by participants. First, we observed a reduced RT1 in the reward compared with the no-reward condition. Furthermore, the reward effects increased on RT2 for short compared with long SOAs, reflecting effect propagation at short SOA from Task 1 onto Task 2. Second, RTs decreased with increasing CTI, while reward effects increased with increasing CTI. Consequently, preparation-related processing improvements of DT performance were *additionally* improved by reward utilization. For Experiment 2, temporal predictability of Task 1 onset was reduced compared with Experiment 1 by presenting CTIs randomized within blocks, which allowed replicating the result pattern of Experiment 1. Across both experiments, the results indicate that participants can flexibly utilize reward information in a trial-by-trial manner and that reward utilization *additionally* improves preparation-related processing improvements for DT conditions with predictable and less predictable Task 1 onset.

Keywords Dual-tasking · Reward utilization · Motivation · Temporal preparation

Introduction

The execution of two tasks in close temporal succession is difficult for humans. In such dual-task (DT) situations, participants' performance usually declines compared with when the same tasks are performed apart. The cognitive processing architecture has long been investigated using DT paradigms such as the psychological refractory period (PRP) paradigm. In these PRP situations, participants execute two temporally overlapping choice reaction time (RT) tasks separated by a varying time interval between them (i.e., the stimulus onset asynchrony [SOA]; Pashler, 1994). This task situation usually results in declined performance compared with single-task situations, which are referred to as DT costs. Specifically, these DT costs relate to a performance pattern in which the response times of the second task (Task 2) are increased with decreasing SOA between both tasks. These costs can be explained with the central bottleneck model, which assumes the serial processing of the central response selection stages, while peripheral stages (i.e., perceptual and motor stages) are assumed to be processed in parallel. In contrast, it is assumed that for the short SOA condition, the response selection and motor stage of Task 2 are not processed until the response selection of the first task (Task 1) has been processed. This leads to a delay of Task

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2 processing and explains why the reaction time to Task 2 (RT2) is increased at short SOA and decreases with increasing the SOA between tasks. At the same time, the reaction time to Task 1 (RT1) is assumed to be unaffected by the length of the SOA between Task 1 and Task 2.

Despite the debate about whether the processing limitations during DT have strategic or structural reasons, several factors have been linked to the modulation of DT processing, such as training (Ruthruff et al., 2006; Schubert & Strobach, 2018; Strobach et al., 2014), age (Hein & Schubert, 2004; Strobach et al., 2012), and different combinations of input and output modalities (Hazeltine et al., 2006; Stelzel et al., 2006). A further current question in this line of research is how the prospect of reward affects cognitive processing during DT (Fischer et al., 2018; Han & Marois, 2013; Rieger et al., 2021).

Previous investigations revealed that the prospect of reward for either Task 1 or Task 2 performance in a PRP DT situation leads to substantial DT improvements (i.e., reduced RT1 and RT2 in the reward compared with the no-reward conditions; Langsdorf et al., 2022, 2025). In these studies, the prospect of reward was manipulated blockwise. In detail, before each reward block, participants were instructed that they could receive a reward for fast and accurate Task 1 performance while minding low error rates on Task 2 performance. Importantly, in these reward blocks, each trial was reward-relevant reflecting a constant prospect of reward for the participants. Thus participants could apply a constant strategy of reward-induced preparation for an entire reward block to obtain a reward. In contrast, it remains unclear whether participants can utilize randomly changing trial-wise reward information and whether the prospect of reward can rapidly build up to improve DT performance (Fischer et al., 2018; Rieger et al., 2021; Yildiz et al., 2013). A further central yet open aspect is whether the utilization of reward information is affected by the length of the preparatory interval, or whether this is not the case. We addressed these open questions, investigating as a first aim of the present study whether participants can flexibly utilize the prospect of reward from trial to trial, as indicated by a cue. For the second and more central aim, we focused on the investigation of the temporal dynamics of reward utilization for behavioral adjustments in DT situations.

By now, there is consensus in the field that cueing the prospect of reward before a trial improves preparatory processes leading to enhanced task performance as reflected by reduced RTs (Chiew & Braver, 2016). In addition, physiological evidence indicates that the prospect of reward can improve motor preparation as well as modulate pupil dilation reflecting preparatory effort (Bundt et al., 2016; Chiew & Braver, 2013). Further evidence stems from event-related potentials (ERPs) with high temporal resolution indicating an earlier onset of task-related preparation processes in a reward compared with a no-reward condition (Schevernels et al., 2014). This questions the idea that reward effects on task performance go beyond pure preparation-related performance improvements (e.g., Rieger et al., 2021; Zedelius et al., 2012). In sum, accumulating evidence indicates a close link between reward-related and preparation-related processing improvements. However, further investigations are still required that investigate in more detail the temporal dynamics of reward utilization.

Related to that, Kleinsorge (2001), provided evidence for the assumption that the length of preparatory intervals affects the reward utilization of participants for processing improvements. In this study, participants were asked to discriminate letters, while at varying intervals before letter presentation, a cue was presented, which signaled whether or not to exhibit additional mental effort. If participants would respond with increased response speed, while committing few errors, they would receive a monetary reward. These so-called effort trials amounted to 20% of trials while the remaining 80% of trials were so-called standard trials. The author reported that with a preparatory interval between 600 and 900 ms, before letter onset, reward utilization for effort trials peaked, while the length of the preparatory interval did not improve task performance for the standard trials. Taken together, the results provide evidence for the assumption that the prospect of reward can be more effectively utilized with an increasing preparatory interval (see also Chiew & Braver, 2016; Falkenstein et al., 2003). Similarly, Chiew and Braver (2016) suggested that increased preparatory intervals enable improved encoding and processing of the reward information for processing improvements. However, it remains an open issue whether similar processing improvements would emerge in DT situations, because these task conditions are more demanding compared with single-task conditions. Furthermore, it remains an open issue whether participants could improve their task performance in a larger proportion of trials, because in previous studies effort trials were reduced in number compared with standard trials (Falkenstein et al., 2003; Kleinsorge, 2001; Steinborn et al., 2017).

A suitable methodological approach, for studying the temporal dynamics of reward utilization can be adapted from studies investigating temporal preparation in sensory-motor RT tasks (see also Falkenstein et al., 2003; Kleinsorge, 2001). In these experiments, preparatory intervals with varying lengths are presented before the target onset. The application of varying preparatory intervals enables the investigation of how temporal preparation impacts task performance, leading to a modulation of RTs, reflecting the temporal preparation effect (Niemi & Näätänen, 1981; Steinborn et al., 2017; Teichner, 1954).

In an investigation by Fischer et al. (2007), different levels of preparation for target processing were applied to test the effect of temporal preparation on the size of the subliminal priming (SP) effect. In SP tasks a target requiring a response is preceded by a subliminal prime, which is either associated with the same motor response (congruent), or with the opposite motor response (incongruent), as the target. Usually, this results in improved RTs in the congruent compared with the incongruent condition, while the SP effect is the difference in RTs of incongruent and congruent trials.

Fischer et al. (2007) presented either an accessory tone stimulus or no tone (serving as the control condition) followed at varying intervals by the presentation of a prime–target pair for which participants were asked to discriminate the pointing direction of the target arrow. For Experiment 1, a randomized presentation of tone–target intervals was applied inducing temporal uncertainty in the participants as they could not establish a precise temporal expectation of target onset. In contrast, for Experiment 2, a blocked presentation of tone–target intervals was chosen, resulting in temporal certainty of target onset. The application of a randomized and blocked presentation of tone–target intervals enabled Fischer et al. (2007) to explore how temporal expectation and temporal preparation jointly affect the SP effect.

The results across both experiments indicated improved task performance in the congruent compared with the incongruent condition. Furthermore, in comparison to the no-tone condition, the size of the SP effect in the tone condition increased with increasing preparation time. These results indicate that the tone stimulus was utilized as a temporal reference for response preparation during the preparatory intervals. The authors inferred that for longer preparatory intervals in contrast to shorter preparatory intervals, an enhanced pre-motoric response activation for stimulus processing can have occurred (Niemi & Näätänen, 1981; Steinborn et al., 2017). Taken together Fischer et al. (2007) provided evidence for the assumption that a temporal reference in combination with temporal preparation can improve the pre-motoric response activation leading to enhanced task performance in an SP task.

The assumption of a pre-motoric locus of the temporal preparation effect was further supported by the findings of studies applying electrophysiological methods. In particular, MÜller-Gethmann et al. (2003) measured motor-related ERPs and reported an effect of temporal preparation on the stimulus-locked lateralized readiness potential (sLRP), which is considered to reflect processes before motor execution. In contrast, no effects of temporal preparation on the response-locked LRP (LRPr) were obtained which is considered to reflect processes related to motor execution. This pattern of results indicates an effect of temporal preparation on early pre-motoric processes and is in line with the assumptions and findings of Fischer et al. (2007; Bausenhart et al., 2006; Hackley & Valle-Inclán, 1998; Jepma et al., 2009).

A further specification of the pre-motoric locus of the temporal preparation effect stems from the application of an accumulation model of human information processing by Grice (1968). The model describes the process of information accumulation with three parameters: 1) the onset of information accumulation, 2) the rate of information accumulation, and 3) the internal decision criterion. In an empirical investigation, Seibold et al. (2011) provided evidence for the assumption that temporal preparation improved the onset of sensory information accumulation in a sensory-motor RT task. The authors concluded that an earlier onset of the sensory information accumulation for task conditions of high temporal preparation compared with low temporal preparation led to a faster reaching of the decision criterion. Taken together, converging evidence of studies applying different methodologies for investigating the temporal preparation effect indicates that temporal preparation improves pre-motoric processes as early as the onset of sensory information accumulation (Bausenhart et al., 2010; Rolke & Hofmann, 2007).

The present study had two research aims: first, we investigated whether participants can flexibly utilize a trial-wise reward prospect for their Task 1 performance. In the corresponding paradigm, a cue indicating whether or not the current trial is reward-relevant is presented shortly before Task 1. Importantly, cue identity varies randomly from trial to trial and participants need to adapt their reward utilization as well between different trials. If participants flexibly utilize the trial-wise reward information then the resulting RT pattern should resemble the RT pattern of previous studies in which the prospect of reward was applied for participants' Task 1 performance but was implemented block-wise. For such a case, we predict an improved RT1 in the reward compared with the no-reward condition, as well as larger reward effects on RT2 at short compared with long SOA. According to the effect propagation logic, such an RT pattern emerges, if the processing stages of Task 1 before or/at the bottleneck are shortened leading to an improved RT1 (see Fig. 1). As a result, the change in the processing duration will be propagated via the bottleneck mechanism onto the Task 2 processing chain, improving also RT2 (Johnston & Pashler, 1990; Langsdorf et al., 2022; Schubert, 1999). Consequently, the effects on RT2 should be increased at short compared with long SOA, as the lack of the bottleneck mechanism at long SOA prevents the propagation of RT changes of the processing stages before or/at the bottleneck of Task 1 onto Task 2. Taken together, this should result in a main effect of reward on RT1 and an overadditve interaction of reward and SOA on RT2, with larger reward effects at short compared with long SOA. The emergence of such an RT1 and RT2 pattern would suggest, that participants were able to flexibly utilize reward information for processing improvements from trial-to-trial and this would represent a good starting point for elucidating the temporal dynamics of reward utilization.

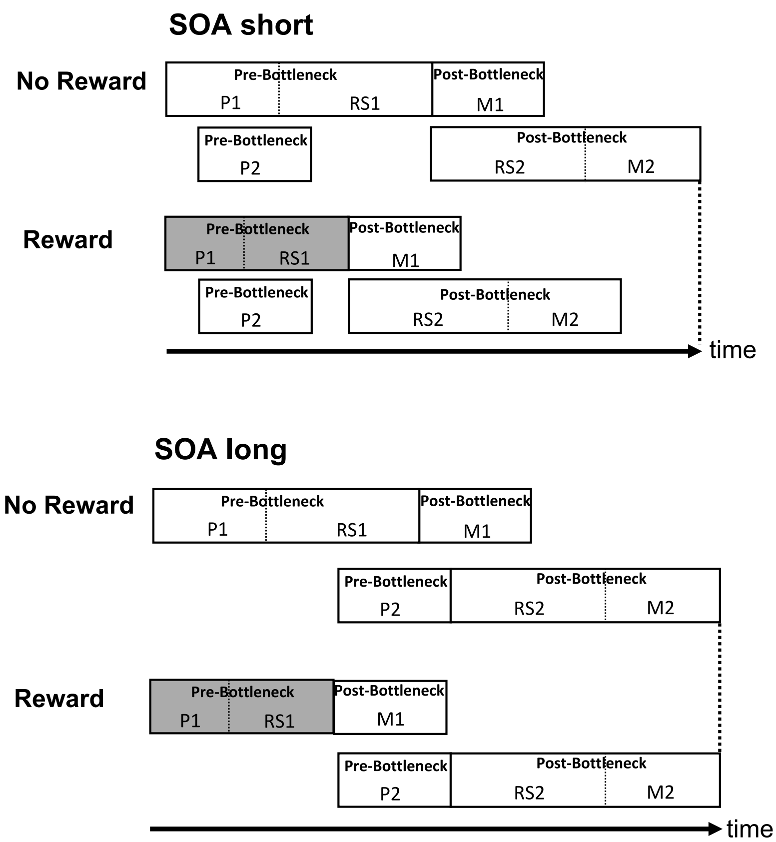

Fig. 1 Depiction of the case when reward reduces the processing time of the pre- and/or bottleneck stages of Task 1, in the reward compared with the no-reward condition. The gray-shaded areas of Task 1 indicate that reward shortens the pre- and/or bottleneck stages of Task 1. P1 = perception stage of Task 1; Bottleneck stage of Task 1 comprises: RS1 = response selection of Task 1. Post-Bottleneck stage of Task 1 comprises M1 = Motor stage of Task 1; Pre-Bottleneck stage of Task 2 comprises: P2 = perception stage of Task 2; Bottleneck stage of Task 2 comprises: RS2 = response selection stage of Task 2; Post-Bottleneck stage of Task 2 comprises: M2 = motor stage of Task 2; SOA = stimulus-onset asynchrony

For the second and more central research aim, we investigated the temporal dynamics of reward utilization. To that end, the size of the reward effect for participants' Task 1 performance was compared between different durations of the cue–tasrget interval (CTI), which was manipulated between blocks (i.e., of either 200 ms or 700 ms). In *each* DT trial, a cue was presented, signaling to the participants whether or not the upcoming DT trial would be reward-relevant, leading to a 50/50 proportion of reward and no-reward trials. As a result, this enabled participants to utilize the cue as a temporal reference for response preparation in the reward and no-reward conditions. However, in the reward condition, the cue could additionally (i.e., compared with the temporal preparation-related effects) improve response processing by stimulating reward-related performance improvements.

Concerning the issue of the temporal dynamics of reward utilization several predictions can be derived. Under the assumption, that participants can flexibly utilize reward information between trials, it is conceivable that the utilization of reward information improves with an increasing preparatory interval, following the results of Kleinsorge (2001) from single-task situations (and others: Chiew & Braver, 2016; Falkenstein et al., 2003). If that was the case, the utilization of reward information should *further* increase with an increasing length of the preparatory interval, resulting in larger reward effects for the long CTI compared with the short CTI condition on RTs. For the current case, in each trial, a cue was presented that participants could utilize as a temporal reference for response preparation. If, in addition, the cue signaled the prospect of reward in the long CTI condition, DT performance in the reward compared with the no-reward condition should improve to a larger extent compared with the short CTI condition.[1] This would result in larger reward effects in the long compared with the short CTI condition on RTs, as reflected by an overadditive interaction of CTI and reward on RTs.

Now let us consider the scenario in which reward utilization improves with increasing CTI, while temporal preparation is also optimized as CTI increases. Improved temporal preparation would manifest as shorter RTs in the long CTI compared with the short CTI condition by itself. In this context, a combined effect of both (i.e., of temporal preparation and reward) would be characterized by an overadditive interaction between CTI and reward on RTs, alongside a main effect of CTI on RTs. Such a pattern would indicate that reward utilization enhances task performance beyond temporal preparation alone. In other words, such a pattern would mean that optimally prepared RTs would further benefit from improved reward utilization in the long CTI condition compared with the short CTI condition. Such findings would challenge the assumption that reward-related processing improvements are solely attributable to preparation-related optimization processes (e.g., Rieger et al., 2021; Zedelius et al., 2012). Instead, such findings would suggest the presence of an additional optimization process, potentially involving enhanced information processing.

As a further alternative, we should also consider that participants may lack the ability to flexibly utilize reward information for processing improvements on a trial-by-trial basis at all. Such an assumption could also be derived as previous DT studies investigating reward processing only applied variants of block-wise reward manipulations (Fischer et al., 2018; Langsdorf et al., 2022, 2025; Rieger et al., 2021; Yildiz et al., 2013). If this was the case, participants' reward utilization would likely remain ineffective regardless of the CTI condition. As a result, no significant differences would be expected between the reward and no-reward conditions for either CTI condition on RTs.

To investigate the temporal dynamics of reward utilization in more detail, we *additionally* focused on the analysis of the RT distribution. In particular, a Vincentized cumulative RT distribution analysis enables one to observe the effects of a reward and the preparation manipulation on the percentiles of the RT distribution. Thus, providing a more fine-grained tool for the interpretation of the potential effects on the mean RTs (Ratcliff, 1979; Schubert et al., 2002; Steinborn et al., 2017). Consequently, we analyzed whether the effects on the RT mean are driven by the speed-up of RTs at the different tails of the distribution. We hypothesized that during optimally prepared trials with shorter RTs cognitive processes are executed efficiently, thus no further improvements are expected by the prospect of reward, irrespective of the CTI condition (De Jong, 2000). In contrast, during trials with longer RTs, i.e. the right tail of the distribution, the prospect of reward might further optimize the cognitive processing chain. This is conceivable since earlier studies reported an effect of mental effort on the right tails of the RT distribution, assuming improved attentional mobilization behind this effect (Steinborn et al., 2017; Strayer et al., 2024). Concerning the current investigation, the effect of reward prospect on the right tail could be more pronounced in the long CTI condition compared with the short CTI condition, as the effect of reward prospect might build up over time, leading to increased reward effects. This effect pattern would indicate that the utilization of reward information is improving with increasing CTI.

Experiment 1

In Experiment 1, we investigated two research aims, first, we tested whether participants could flexibly utilize a trial-wise reward prospect for their Task 1 performance. Second, we were interested in the temporal dynamics of reward utilization. To that end, we administered a cue in the reward and the no-reward condition before Task 1 presentation and manipulated the CTI block-wise either for 200 ms or 700 ms. The task situation comprised of an auditory-visual DT which was separated by one of three SOAs (100 ms, 300 ms, or 900 ms). Furthermore, participants were instructed that they could earn a monetary reward if their response to Task 1 was fast and accurate while maintaining a low error rate in Task 2.

Materials and methods

Participants

Twenty-five healthy participants (21 women; $M_{age} = 22$ years) were invited to take part in the experiment after obtaining written informed consent and were debriefed after the session. We used the *superpower* R package (Lakens & Caldwell, 2021) a Monte Carlo simulation-based

[1] It must be noted that the time for cue discrimination and for deciding on effort mobilization in the reward condition needs also to be considered when assessing the time available for reward utilization under the conditions of short and long CTI. Therefore, the resulting time available for reward utilization is even shorter than the nominal time of 200 ms and 700 ms in the two CTI conditions. We thank an anonymous reviewer for pointing this out. This needs to be also considered when specifying the hypotheses in cue-related reward tasks.

tool for conducting power analyses[2] for multifactorial within-designs. To estimate the required sample size for the interaction effect of the factors reward and CTI on RTs (i.e., a larger reward effect in the long CTI condition compared with the short CTI condition). Absolute RTs for each cell, standard deviations, and correlation coefficients among within-subject factors were estimated based on a pilot study and a previous DT investigation (Langsdorf et al., 2022). Setting $\alpha = 0.05$, the simulation analysis yielded a sample size of $N = 25$ for detecting an interaction effect with the power of 90%. The experimental protocol conformed to the declaration of Helsinki. All participants were right-handed, German native speakers, and had normal or corrected-to-normal vision. Furthermore, participants could choose between 4 euro or course credit as a general payment, which was added to the performance-dependent amount of monetary reward (see below).

Apparatus and stimuli

Participants performed a PRP DT consisting of an auditory and a visual choice RT task. Stimuli for the auditory task comprised three sine-wave tones with a frequency of 250, 500, or 1000 Hz presented for 200 ms via headphones. Participants responded to the low-, middle-, and high-pitched tones by pressing the ‘Y’, ‘X’, and ‘C’ keys of a QWERTZ keyboard with the ring, middle, and index fingers of their left hand, respectively. For the visual task, one of three digits (1, 5, or 9) was presented centrally on a computer screen with a visual angle of $1.07° \times 1.07°$ at a viewing distance of 80 cm. Visual stimuli appeared for 200 ms, and participants responded to the digits in ascending order by pressing the keys ‘M’, ‘,’, and ‘.’ of a QWERTZ keyboard with the index, middle, and ring finger of their right hand, respectively. Participants were instructed to first respond to the auditory and then to the visual task. Each trial started with the presentation of a fixation cross at the center of the screen for 950 ms followed by a white or blue ring with a visual angle of $2.15° \times 2.15°$ (indicating either a reward or no-reward trial) for 200 ms followed by a blank interval of either 0 ms or 500 ms, depending on the CTI condition of 200 ms or 700 ms. Subsequently, the auditory stimulus was presented for 200 ms, followed by the visual stimulus for 200 ms, separated by an SOA of either 100 ms, 300 ms, or 900 ms. After a response to both target stimuli or a maximal response duration of 3,000 ms, an intertrial interval of 500 ms followed before the start of the next trial. Participants received the feedback “Falsch” (German for *wrong*) for 500 ms if either one or two of their responses were erroneous. If their response to either target exceeded the maximal response duration, the feedback “Zu langsam” (German for *too slow*) was presented for 500 ms. If participants responded first to the digit task, the feedback “Reihenfolge beachten” (German for *mind response order*) was presented for 500 ms.

Design and procedure

We applied a three-factorial within-subjects design, with reward, CTI, and SOA as independent variables. Each block consisted of 54 trials resulting from the combination of two reward levels (reward or no reward), three SOAs (100 ms, 300 ms, 900 ms), three auditory stimuli (250 Hz, 500 Hz, 1000 Hz), and three visual stimuli (1, 5, 9). In total, six DT blocks were presented comprising three DT blocks with a CTI of 200 ms and three DT blocks with a CTI of 700 ms, resulting in 324 experimental trials.

The procedure was as follows: The experiment started with a single-task practice phase in which participants performed 12 single-task trials for each component task (auditory and visual). The timing of these single-task trials was identical to DT trials with the exception that only one target stimulus was presented and only one response was required. These single-task trials were followed by two blocks of 54 trials of DT practice one block for each CTI condition. At the start of the DT practice, participants were instructed to respond to Task 1 as soon as it was presented (Ulrich & Miller, 2008).

After that, participants entered the reward phase of the experiment. For that purpose, they were instructed that their Task 1 performance was rewarded with 72 euro cents per block. They would receive a reward if their response to Task 1 was fast and accurate, while their Task 2 performance was not rewarded (to mind low error rates on Task 2). The color of the cue signaled either a reward or no-reward trial presented either in white or blue (counterbalanced across participants). The information about the cue–reward mapping and the reward scheme was again presented before each block. Furthermore, the experiment only proceeded after the participants had verbally reported the cue–reward mapping and the reward scheme (Chiew & Braver, 2016). For the first reward block, we set a pre-defined threshold of 850 ms for Task 1 performance as well as 89% accuracy, based on previous studies (Langsdorf et al., 2022; and pilot studies). Subsequently, participants' thresholds for earning a reward were continuously calculated based on their mean RT1 performance and their mean error rates in reward blocks.

If in the first reward block either participants' mean RT1 or their mean error rates met the pre-defined threshold, they received 72 euro cents. If none of their performance measures were below the pre-defined thresholds, they received no reward. Thereafter, the threshold RT1 was

[2] We applied the identical power analysis for Experiment 2. Therefore, the estimated sample size of $N = 25$ holds for Experiment 2, as well.

updated by averaging the pre-defined threshold (850 ms) and the mean RT1 of the previous reward block. Similarly, the mean error rate was updated. Subsequently, only the performance measures from the reward blocks were used to compute individual thresholds for obtaining a reward. After each block, participants received feedback about their mean RT1 and percentage of correct trials, and whether they earned a reward (and how much reward they had earned so far). Finally, participants were naïve about the threshold computations for obtaining a reward.

Statistical analysis

Mean RTs and error rates were analyzed separately for RT1 and RT2 using an analysis of variance (ANOVA) with the within-subjects factors reward, SOA, and CTI. A significance threshold of 5% was used for all analyses. The *p* values of the ANOVAs were adjusted according to the Greenhouse–Geisser correction when necessary (Huynh, 1978). For the RT analyses, trials with at least one erroneous response ($M = 7.7\%$) and outliers that deviated more than ± 2.5 standard deviations (*SD*s) for each participant and factor combination ($M = 4.9\%$) were excluded from the data set. Furthermore, trials were excluded that met the criterion of response grouping (RT2 − RT1 + SOA) < 200 (Ulrich & Miller, 2008). All analyses and visualizations were conducted in R and ggplot2 relying on the tidyverse dialect (R Core Team, 2021; Wickham, 2011; Wickham et al., 2019).

Results

Task 1

We first tested for the effects of reward on Task 1 performance. We obtained a significant main effect of the factor reward, $F(1, 24) = 18.26$, $p < 0.001$, $\eta_G^2 = 0.053$. Participants' RT1 was reduced in the reward ($M = 546$ ms) compared with the no-reward ($M = 583$ ms; see Fig. 2) condition. The interaction of the factors reward and SOA reached significance, $F(2, 48) = 3.90$, $p < 0.027$, $\eta_G^2 = 0.004$, with marginally increased reward effects at SOA 100 ($M = 51$ ms) compared with SOA 300 ($M = 33$ ms), $t(24) = 2.01$, $p = 0.056$, and larger reward effects compared with SOA 900 ($M = 29$ ms), $t(24) = 2.57$, $p < 0.017$. Taken together these reward effects indicate that participants were utilizing the reward information to improve their DT performance. Furthermore, we obtained a significant main effect of the factor SOA, $F(2, 48) = 9.84$, $p < 0.001$, $\eta_G^2 = 0.026$, on RT1, with an increasing RT1 for shorter SOAs. Such effects of SOA on Task 1 are often explained by participants' tendency for response grouping (Strobach et al., 2015; Ulrich & Miller, 2008). In addition, we obtained a significant main effect of the factor CTI, $F(1, 24) = 21.76$, $p < 0.001$, $\eta_G^2 = 0.038$, with a reduced RT1 in the long CTI ($M = 548$ ms) compared with the short CTI ($M = 577$ ms) condition, indicating the typical preparation effect on RT1 performance (Niemi & Näätänen, 1981).

Most importantly for the issue of the temporal dynamics of reward utilization, we obtained a significant overadditive interaction of the factors reward and CTI on RT1, $F(1, 24) = 4.76$, $p < 0.039$, $\eta_G^2 = 0.002$. In particular, the reward effect in the long CTI condition ($M = 45$ ms) was increased compared with the short CTI condition ($M = 30$ ms). This effect pattern is in line with the assumption that the utilization of reward information improves with increasing CTI duration. Furthermore, we obtained a marginally significant three-way interaction of the factors reward, CTI, and SOA, $F(2, 48) = 3.03$, $p = 0.058$, $\eta_G^2 = 0.003$. That showed a trend towards larger reward effects for SOA 100 in the long CTI condition, compared with the short CTI condition. The interaction of the factors SOA and CTI, $F(2, 48) = 0.18$, $p = 0.840$, $\eta_G^2 < 0.001$, did not reach significance.

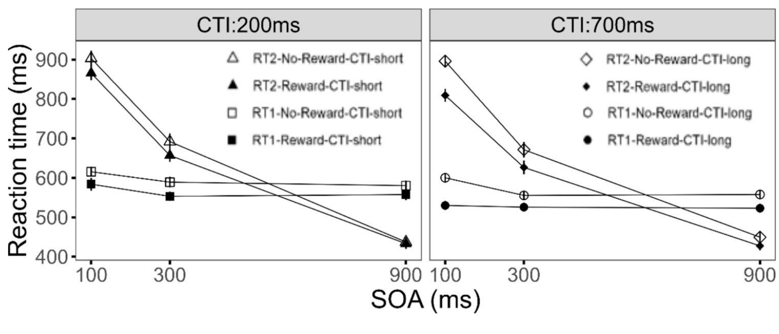

Fig. 2 Mean RTs for Task 1 and Task 2 as a function of reward, stimulus-onset asynchrony (SOA), and cue–target interval (CTI) for Experiment 1. Error bars represent the standard error of the mean

Effects on the distribution of RT1

To further elucidate the temporal dynamics of reward utilization, we conducted a distribution analysis of RT1. Our reasoning focused on the potential performance improvements at the different tails of the RT distribution. Here we assumed, that in trials with shorter RTs (i.e., the left tail), cognitive processes are optimally executed and thus no further or only slight improvements are obtainable by the prospect of reward, irrespective of the CTI condition. In contrast, during trials with longer RTs (i.e., the right tail), the prospect of reward might further optimize the cognitive processing chain. Such an effect pattern might be more pronounced in the long CTI compared with the short CTI condition, as the effect of reward prospect might evolve leading to increased reward effects on RT1.

For this purpose, the RT1 was rank-ordered from slowest to fastest. Subsequently, the means were computed for each factor combination and RT1 was corrected for outliers (± 2.5 *SD*). After that, the percentiles (10 equal bins) for each factor combination were computed based on the outlier corrected RT1, and subsequently the means were calculated (Schubert, 1999). The mean RT1 for the respective factor combination is plotted on the *x*-axis, while the cumulative distribution is plotted on the *y*-axis (i.e., the respective percentile from 1 to 10 (see Fig. 3). For statistical computations, the factor percentile was used along with the factors reward, SOA, and CTI in an ANOVA. However, to avoid redundancy, we will report only the statistical parameters for effects that include the factor *percentile*. This decision is based on the corresponding results of the previously reported analysis of mean RTs and the results of the current distributional analysis.

First, we obtained a three-way interaction of the factors reward, CTI, and percentile, $F(9, 216) = 2.01$, $p < 0.039$, $\eta_G^2 = 0.002$. As depicted in Fig. 3 the reward effects were larger in the long CTI compared with the short CTI condition. This pattern was further specified as the reward effects increased with increasing RT1. This effect indicates that the reward effect increased with a longer CTI and that longer RTs were affected in particular. In sum, this suggests that during trials with longer RTs, the impact of the reward prospect in the long CTI condition on cognitive processes was increased.

In addition, the reward effects increased as RT1 got slower. This observation was confirmed by a significant interaction of the factors reward and percentile on RT1, $F(9, 216) = 6.73$, $p < 0.001$, $\eta_G^2 = 0.007$. Furthermore, the factor percentile reached significance, $F(9, 216) = 229.01$, $p < 0.001$, $\eta_G^2 = 0.591$. The interaction of the factors SOA and percentile reached also significance, $F(18, 432) = 12.83$, $p < 0.001$, $\eta_G^2 = 0.022$.

Neither of the following interactions reached significance. The interaction of the factors percentile and CTI did not reach significance, $F(9, 216) = 1.39$, $p = 0.192$, $\eta_G^2 = 0.001$. Similarly, the interaction of the factors percentile, reward, and SOA was nonsignificant, $F(18, 432) = 0.99$, $p = 0.466$, $\eta_G^2 = 0.001$. The interaction of the factors percentile, CTI, and SOA did not reach significance, $F(18, 432) = 0.11$, $p = 0.984$, $\eta_G^2 < 0.001$. The four-way interaction of the factors percentile, reward, CTI, and SOA did not reach significance, $F(18, 432) = 0.77$, $p = 0.738$, $\eta_G^2 < 0.001$.

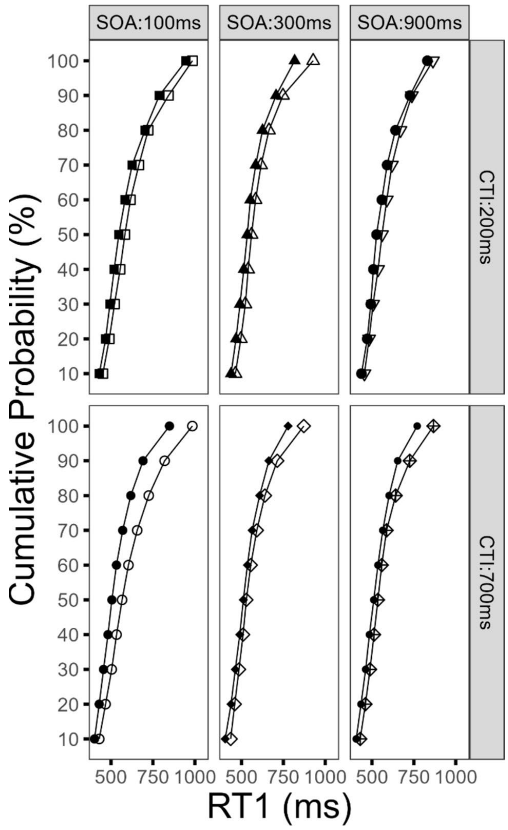

Fig. 3 Analysis of reaction time distribution for Task 1 (RT1) as a function of percentile, reward, stimulus-onset asynchrony (SOA), and cue–target interval (CTI) for Experiment 1. Filled symbols denote the reward condition. Empty symbols denote the no-reward condition

For the error rates in Task 1, we obtained neither a significant main effect nor a significant interaction (see Table 1). The main effect of the factor reward did not reach significance, $F(1, 24) = 2.22$, $p = 0.149$, $\eta_G^2 = 0.004$. Furthermore, the interaction of the factors reward and CTI also did not reach significance, $F(1, 24) = 1.69$, $p = 0.206$, $\eta_G^2 = 0.003$. Furthermore, the three-way interaction of the factors reward, CTI, and SOA did not reach significance, $F(2, 48) = 1.69$,

Table 1 Mean rates of errors for Task 1 and Task 2 in % (and standard error of the mean) from Experiment 1 as a function of reward, stimulus-onset asynchrony (SOA), and cue–target interval (CTI)

	Experiment 1									
	Reward-CTI									
	Reward – Short CTI		No Reward – Short CTI		Reward – Long CTI				No Reward – Long CTI	
SOA	Task 1	Task 2	Task 1	Task 2	Task 1	Task 2			Task 1	Task 2
100	6.2% (.7%)	2.8% (.5%)	6.1% (.9%)	2.8% (.8%)	6.6% (.9%)	3% (.7%)			5.9% (.9%)	3.0% (.6%)
300	5% (.8%)	3% (.5%)	5.8% (.8%)	3% (.6%)	7.5% (1.1%)	2.8% (.6%)			4.4% (.6%)	2.4% (.5%)
900	5.9% (.9%)	3.6% (.7%)	5% (.9%)	2.7% (.9%)	4.9% (1.1%)			3.1% (.7%)	4.9% (.8%)	2.8% (1%)

$p=0.195$, $\eta_G^2=0.008$. Furthermore, the factor SOA did not reach significance, $F(2, 48)=1.06$, $p=0.356$, $\eta_G^2=0.006$. The factor CTI did not reach significance, $F(1, 24)=0.01$, $p=0.922$, $\eta_G^2<0.001$. The interaction of the factors reward and SOA also did not reach significance, $F(2, 48)=0.22$, $p=0.806$, $\eta_G^2=0.001$.

Task 2

Next, we tested how Task 2 performance was affected by reward. We obtained a significant main effect of the factor reward, $F(1, 24)=21.47$, $p<0.001$, $\eta_G^2=0.025$, on RT2. Participants responded faster in the reward ($M=635$ ms) compared with the no-reward ($M=673$ ms; see Fig. 2) condition. Furthermore, we found a significant main effect of the factor SOA, $F(2, 48)=271.38$, $p<0.001$, $\eta_G^2=0.683$. RT2 increased from SOA 900 ($M=438$ ms) to SOA 100 ($M=867$ ms), indicating the typical PRP effect (Pashler, 1994). In addition, we found a significant main effect of the factor CTI, $F(1, 24)=7.61$, $p<0.011$, $\eta_G^2=0.006$, on RT2. Participants responded faster in the long CTI condition ($M=644$ ms) compared with the short CTI condition ($M=664$ ms), reflecting the temporal preparation effect on RT2 performance (Niemi & Näätänen, 1981).

Furthermore, we obtained a significant overadditive interaction of the factors reward and SOA, $F(2, 48)=11.86$, $p<0.001$, $\eta_G^2=0.007$, on RT2. Pair-wise comparisons revealed a significantly larger reward effect for SOA 100 ($M=62$ ms) compared with SOA 900 ($M=13$ ms), $t(24)=5.175$, $p<0.001$. This overadditive interaction of reward and SOA on RT2 is consistent with the assumption of effect propagation from Task 1 onto Task 2, improving RT2 as well. This is in line with previous evidence, indicating that the prospect of reward affected the pre- and/or bottleneck stages of Task 1 (Langsdorf et al., 2022).

Central for the issue of how reward utilization is affected by the temporal duration of the CTI condition, we obtained a significant overadditive interaction of the factors reward and CTI on RT2, $F(1, 24)=9.43$, $p<0.005$, $\eta_G^2=0.003$. We obtained larger reward effects in the long CTI condition ($M=51$ ms) compared with the short CTI condition ($M=26$ ms). We further obtained a trend for a significant three-way interaction of the factors reward, CTI, and SOA on RT2, $F(2, 48)=2.63$, $p=0.083$, $\eta_G^2=0.002$. This effect hints at larger reward effects in the long CTI condition at SOA 100 compared with the reward effects at SOA 100 in the short CTI condition. Taken together, these effects are consistent with the assumption that the utilization of reward information improves with increasing CTI duration.

Finally, we obtained an overadditive interaction of the factors CTI and SOA, $F(2, 48)=7.09$, $p<0.002$, $\eta_G^2=0.004$. Further tests indicated a larger CTI effect ($M=31$ ms) for SOA 100 compared with SOA 900 ($M=-3$ ms), $t(24)=3.208$, $p<0.001$. This result indicates that temporal preparation affected the processing stages before or/at the bottleneck of Task 1, leading to effect propagation onto Task 2, affecting also RT2 (Bausenhart et al., 2006).

Effects on the distribution of RT2

The subsequent analysis focused on the temporal dynamics of reward utilization and the observable effects on the distribution of RT2. For this purpose, we conducted a Vincentized distribution analysis (identical procedure as for Task 1) and added the factor percentile to the factors reward, SOA, and CTI in an ANOVA. In order to avoid redundancy, we will report only the statistical parameters for effects that include the factor *percentile*, for the previously indicated reason.

First, we obtained a significant three-way interaction of the factors reward, CTI, and percentile, $F(9, 216)=3.31$, $p<0.031$, $\eta_G^2=0.001$. As depicted in Fig. 4, the reward effects increased in the long CTI compared with the short CTI condition. Furthermore, these reward effects increased

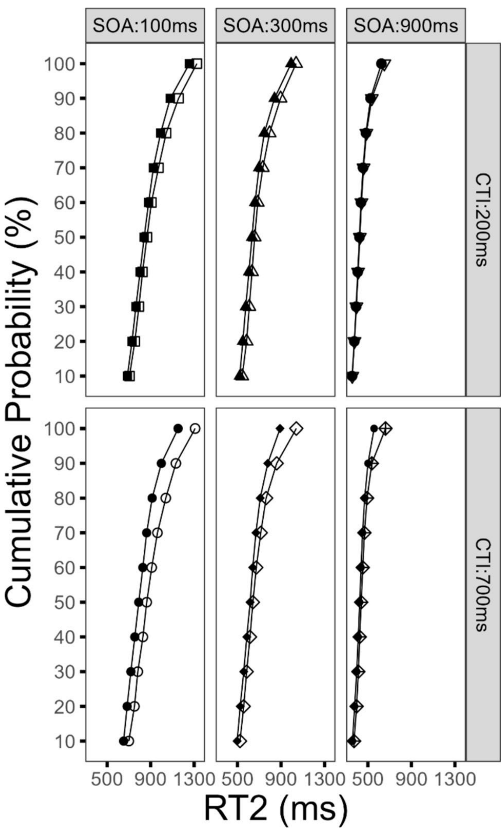

Fig. 4 Analysis of reaction time distribution for Task 2 (RT2) as a function of percentile, reward, stimulus-onset asynchrony (SOA), and cue–target interval (CTI) for Experiment 1. Filled symbols denote the reward condition. Empty symbols denote the no-reward condition

with increasing RT2. This effect demonstrates that the reward effect increased with a longer CTI and that longer RTs were affected in particular. As a result, such an effect pattern could indicate that for trials with longer RTs the impact of the reward prospect on the cognitive processing chain was more effective in the long CTI condition, compared with the short CTI condition.

In addition, the reward effects increased as RT2 got slower. This observation was verified by a significant interaction of the factors reward and percentile on RT2, $F(9, 216) = 7.94$, $p < 0.001$, $\eta_G^2 = 0.006$. Furthermore, the factor percentile reached significance, $F(9, 216) = 278.29$, $p < 0.001$, $\eta_G^2 = 0.450$. The interaction of the factors SOA and percentile also reached significance, $F(18, 432) = 64.92$, $p < 0.001$, $\eta_G^2 = 0.076$. In addition, we obtained a significant interaction of the factors percentile and CTI, $F(9, 216) = 5.30$, $p < 0.001$, $\eta_G^2 = 0.002$.

Neither of the following interactions reached significance. The interaction of the factors percentile, reward, and SOA was nonsignificant, $F(18, 432) = 0.99$, $p = 0.470$, $\eta_G^2 < 0.001$. The interaction of the factors percentile, CTI, and SOA did not reach significance, $F(18, 432) = 0.11$, $p = 0.999$, $\eta_G^2 < 0.001$. Finally, the interaction of the factors percentile, reward, CTI, and SOA was not significant, $F(18, 432) = 0.32$, $p = 0.997$, $\eta_G^2 = 0.001$.

For the error rates on Task 2, we obtained neither a significant main effect nor a significant interaction. The factor reward did not reach significance, $F(1, 24) = 1.37$, $p = 0.253$, $\eta_p^2 = 0.001$. In addition, the interaction of the factors reward and CTI did not reach significance, $F(1, 24) = 0.03$, $p = 0.871$, $\eta_p^2 < 0.001$. Furthermore, the interaction of the factors SOA, reward, and CTI did not reach significance, $F(2, 48) = 0.39$, $p = 0.682$, $\eta_p^2 < 0.001$. The main effect of the factor CTI did not reach significance, $F(1, 24) = 0.29$, $p = 0.596$, $\eta_p^2 < 0.001$. Furthermore, the effect of the factor SOA did not reach significance, $F(2, 48) = 0.10$, $p = 0.903$, $\eta_p^2 < 0.001$. The interaction of the factors reward and SOA did not reach significance, $F(2, 48) = 0.36$, $p = 0.701$, $\eta_G^2 < 0.001$. The interaction of the factors SOA and CTI did not reach significance, $F(2, 48) = 0.19$, $p = 0.828$, $\eta_p^2 < 0.001$.

Discussion

In Experiment 1, participants were able to flexibly utilize the reward information on a trial-to-trial basis to improve their DT performance, as reflected by the main effects of reward on RT1 and RT2. Furthermore, we obtained an overadditive interaction of reward and SOA on RT2, with larger reward effects at short compared with long SOA. These findings are consistent with the assumption that reward affected pre- and/or bottleneck stages of Task 1 improving RT1. As a result, the reward-related processing improvements propagated onto Task 2 at short SOA via the bottleneck mechanism to improve RT2, while for the long SOA condition, no bottleneck emerges preventing the transmission between tasks. This effect pattern suggests that participants were able to flexibly utilize reward information for behavioral DT improvements (Langsdorf et al., 2022).

Importantly, we furthermore obtained results in line with the assumption that the utilization of reward information depends on the temporal duration of the preparatory interval. This is reflected by the overadditive interaction of reward and CTI on mean RT1 and RT2, with larger reward effects in the long CTI compared with the short CTI condition. These results were further substantiated by the results of the RT distribution analysis, with increased reward effects in the long CTI compared with the short CTI condition on RT1 and RT2, especially on longer RTs. These effects indicate that the joint effect of reward prospect and CTI more efficiently optimizes longer RTs in the long CTI condition. Furthermore, these effects where accompanied by a main effect of CTI on RT1 and RT2, reflecting optimized preparation. Consequently, we obtained a combined effect of enhanced reward utilization and improved task preparation. We will come back to these points in the General Discussion section.

For Experiment 2, we aimed to test whether temporal expectation affects the temporal dynamics of reward utilization in Experiment 1. Therefore, we applied the CTIs randomized within blocks, as this reduces the temporal expectation of participants for target onset (Fischer et al., 2007). In contrast, for Experiment 1, a blocked presentation of CTI was applied which should have led to a precise temporal expectation of Task 1 onset by the participants. As a result, the temporal expectation might have affected the temporal dynamics of reward utilization in Experiment 1.

Experiment 2

In Experiment 2, we investigated the temporal dynamics of reward utilization for DT conditions in which participants cannot build up a precise temporal expectation of Task 1 onset. This enabled us to investigate whether temporal expectation affects the temporal dynamics of reward utilization. To this end, we combined a trial-wise reward prospect for participants' Task 1 performance, indicated by a cue signaling either a reward or no-reward trial with a randomized CTI of either 200 ms or 700 ms. Thus, for both CTI conditions, a cue was presented signaling either a reward or no-reward trial. The randomized CTI application increased the temporal uncertainty of the participants, as either a CTI of 200 ms or 700 ms could be presented. Finally, the task situation comprised of an auditory-visual DT with three SOAs (100 ms, 300 ms, or 900 ms). The reward application was identical to Experiment 1 as we instructed participants that they could earn a monetary reward if their response to Task 1 was fast and accurate while minding a low error rate in Task 2.

Materials and methods

Participants

Twenty-five healthy participants (20 women; $M_{age} = 23$ years) were invited to take part in the experiment. One participant had to be excluded due to technical difficulties. The further procedure was identical to Experiment 1.

Apparatus and stimuli

The apparatus and stimuli were identical to Experiment 1. The only exception was that within each DT block the CTIs of 200 ms or 700 ms were randomly presented.

Design and procedure

The design and procedure were identical to Experiment 1.

Statistical analysis

All analyses on the RTs and error rates for Task 1 and Task 2 were identical to Experiment 1. For the RT analyses, trials with at least one erroneous response ($M = 8.3\%$) and outliers that deviated more than ± 2.5 standard deviations for each participant and factor combination ($M = 4.6\%$) were excluded from the data set.

Results

Task 1

We first tested for the effects of reward on Task 1 performance. We obtained a significant main effect of the factor reward, $F(1, 23) = 23.20$, $p < 0.001$, $\eta_G^2 = 0.037$. Participants' RT1 was reduced in the reward ($M = 634$ ms) compared with the no-reward ($M = 696$ ms; see Fig. 5) condition. Furthermore, we obtained a significant main effect of the factor SOA on RT1, $F(2, 46) = 5.76$, $p < 0.006$, $\eta_G^2 = 0.008$, with increasing RT1 for shorter SOAs. These effects of SOA on Task 1 performance are usually explained with strategical response grouping by the participants (Strobach et al., 2015; Ulrich & Miller, 2008). In addition, we obtained a significant main effect of the factor CTI, $F(1, 23) = 68.77$, $p < 0.001$, $\eta_G^2 = 0.025$. Participants´ RT1 was reduced in the long CTI condition ($M = 640$ ms) compared with the short CTI condition ($M = 686$ ms), indicating the temporal preparation effect on RT1 (Niemi & Näätänen, 1981).

Most importantly, for the issue of the temporal dynamics of reward utilization, we obtained a significant overadditive interaction of the factors reward and CTI, $F(1, 23) = 5.12$, $p < 0.033$, $\eta_G^2 < 0.001$, on RT1. The reward effect was increased in the long CTI ($M = 69$ ms) compared with the short CTI ($M = 51$ ms) condition. As a result, this effect pattern is in line with the assumption that the utilization of reward information improves with increasing processing duration for DT conditions of increased temporal uncertainty.

Neither the interaction of the factors reward and SOA reached significance, $F(2, 46) = 0.34$, $p = 0.711$, $\eta_G^2 < 0.001$, nor the interaction of the factors, SOA and CTI, $F(2, 46) = 1.11$, $p = 0.338$, $\eta_G^2 < 0.001$. Finally, we did not obtain

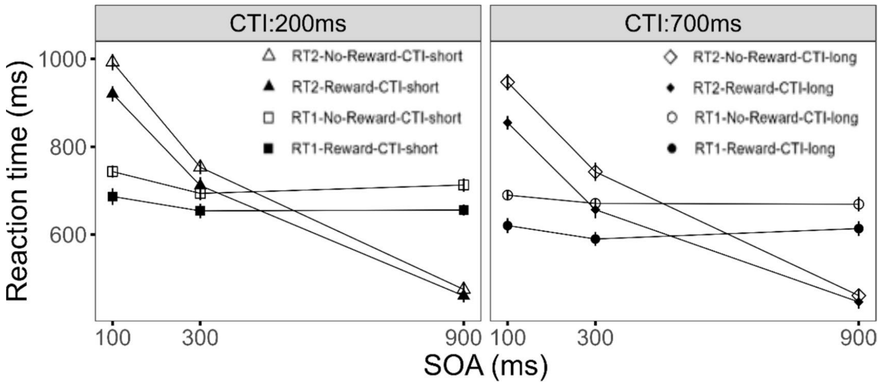

Fig. 5 Mean RTs for Task 1 and Task 2 as a function stimulus-onset asynchrony (SOA), and cue–target interval (CTI) for Experiment 2. Error bars represent the standard error of the mean

a significant three-way interaction of the factors reward, CTI, and SOA, $F(2, 46) = 1.48$, $p = 0.239$, $\eta_G^2 < 0.001$.

Effects on the distribution of RT1

As for Experiment 1, we conducted a Vincentized distribution analysis of RT1 to further investigate the temporal dynamics of reward utilization. The procedure to compute the distribution analysis was identical to the procedure described in Experiment 1. The resulting factor percentile was added along with the factors reward, SOA, and CTI in an ANOVA. With the aim of avoiding redundancy, we will report only the statistical parameters for effects that include the factor *percentile* for the previously indicated reason.

First, we obtained a significant three-way interaction of the factors reward, CTI, and percentile, $F(9, 207) = 2.33$, $p < 0.016$, $\eta_G^2 = 0.002$. As depicted in Fig. 6, the reward effects increased for the long CTI compared with the short CTI condition. This effect was further specified, as the reward effect increased with increasing RT1. This result indicates increased reward effects in the long compared with the short CTI condition, with a stronger benefit for slower RTs, for DT conditions of increased temporal uncertainty.

In addition, the reward effect increased with longer RT1, which is confirmed by the interaction of the factors reward and percentile, $F(9, 207) = 8.11$, $p < 0.001$, $\eta_G^2 = 0.005$. The reward effect pattern demonstrates that the prospect of reward affects specifically longer RTs. We also obtained a significant main effect of the factor percentile, $F(9, 207) = 103.47$, $p < 0.001$, $\eta_G^2 = 0.374$, and a significant interaction of the factors percentile and CTI, $F(9, 207) = 9.62$, $p < 0.001$, $\eta_G^2 = 0.003$.

None of the following interactions reached significance. The interaction of the factors percentile, reward, and SOA did not reach significance $F(18, 414) = 1.12$, $p = 0.325$, $\eta_G^2 < 0.001$. The interaction of the factors percentile, CTI, and SOA did not reach significance, $F(18, 414) = 0.67$, $p = 0.846$, $\eta_G^2 = 0.202$.The interaction of the factors percentile and SOA did not reach significance, $F(18, 414) = 1.27$, $p < 0.202$, $\eta_G^2 = 0.001$.The interaction of the factors percentile, reward, CTI, and SOA did not reach significance, $F(18, 414) = 1.12$, $p = 0.329$, $\eta_G^2 < 0.001$.

For the error rates on Task 1 (see Table 2), we only obtained a significant main effect of the factor SOA, $F(1, 23) = 8.44$, $p < 0.001$, $\eta_G^2 = 0.015$, with increased error rates for SOA 100 ($M = 7\%$) compared with SOA 300 ($M = 5\%$) and SOA 900 ($M = 5\%$). The factor reward did not reach significance, $F(1, 23) = 1.19$, $p = 0.287$, $\eta_G^2 = 0.003$. The interaction of the factors reward and CTI did not reach significance, $F(1, 23) = 0.04$, $p = 0.842$, $\eta_p^2 < 0.001$. Also, the three-way interaction of the factors reward, SOA, and CTI did not reach significance, $F(2, 46) = 0.07$, $p = 0.936$, $\eta_p^2 < 0.001$. The interaction of the factors reward and SOA did not reach significance, $F(2, 46) = 0.01$, $p = 0.980$, $\eta_p^2 < 0.001$. In addition, the interaction of the factors SOA and CTI did not reach significance, $F(2, 46) = 0.39$, $p = 0.679$, $\eta_p^2 < 0.001$.

Task 2

Next we tested for the effects of reward on Task 2 performance**.** We observed a significant main effect of the factor reward on RT2, $F(1, 23) = 52.22$, $p < 0.001$, $\eta_G^2 < 0.019$. Participants responded faster in the reward ($M = 677$ ms) compared with the no-reward condition ($M = 728$ ms; see

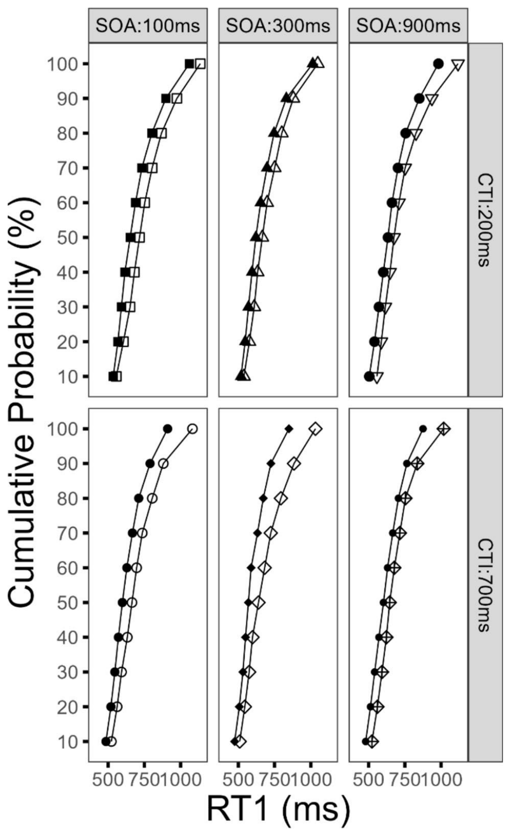

Fig. 6 Analysis of reaction time distribution for Task 1 (RT1) as a function of percentile, reward, stimulus-onset asynchrony (SOA), and cue–target interval (CTI) for Experiment 2. Filled symbols denote the reward condition. Empty symbols denote the no-reward condition

Fig. 5). Furthermore, the factor SOA reached significance, $F(2, 46) = 343.12$, $p < 0.001$, $\eta_G^2 < 0.498$. RT2 increased from SOA 900 ($M = 462$ ms) to SOA 100 ($M = 927$ ms) demonstrating the typical PRP effect (Pashler, 1994). In addition, we obtained a significant main effect of the factor CTI, $F(1, 23) = 45.93$, $p < 0.001$, $\eta_G^2 < 0.008$. Participants responded faster in the long CTI condition ($M = 683$ ms) compared with the short CTI condition ($M = 717$ ms), demonstrating the temporal preparation effect on RT2 (Niemi & Näätänen, 1981).

Most importantly, for the issue of the temporal dynamics of reward utilization, we obtained a significant overadditive interaction of the factors reward and CTI, $F(1, 23) = 4.89$, $p < 0.037$, $\eta_G^2 = 0.001$, on RT2. The reward effects increased in the long CTI ($M = 64$ ms) compared with the short CTI ($M = 43$ ms) condition. This effect is consistent with the assumption that reward utilization improves with increasing CTI for DT conditions of reduced temporal expectation. Furthermore, the three-way interaction of the factors reward, CTI, and SOA did not reach significance, $F(2, 46) = 2.20$, $p = 0.122$, $\eta_G^2 < 0.001$.

Furthermore, we obtained a significant overadditive interaction of the factors reward and SOA, $F(2, 46) = 19.07$, $p < 0.001$, $\eta_G^2 < 0.006$, with larger reward effects at SOA 100 ($M = 82$ ms) compared with SOA 900 ($M = 15$ ms), $t(23) = 6.371$, $p < 0.001$ (Langsdorf et al., 2022). In addition, we obtained a significant overadditive interaction of the factors CTI and SOA, $F(2, 46) = 3.34$, $p = 0.044$, $\eta_G^2 < 0.002$. The CTI effect was increased for SOA 100 ($M = 56$ ms) compared with SOA 900 ($M = 14$ ms), $t(23) = 2.724$, $p < .012$ (Bausenhart et al., 2006). These effects are in line with the results of Experiment 1 and the remarks from the introduction section, suggesting a premotoric locus of the reward and temporal preparation effect on Task 1 processes.

Table 2 Mean rates of errors for Task 1 and Task 2 in % (and standard deviation) from Experiment 2 as a function of reward, stimulus-onset asynchrony (SOA), and cue–target interval (CTI)

	Experiment 2								
	Reward-CTI								
	Reward – Short CTI		No Reward – Short CTI		Reward – Long CTI			No Reward – Long CTI	
SOA	Task 1	Task 2	Task 1	Task 2	Task 1	Task 2		Task 1	Task 2
100	6.3% (1.3%)	3.2% (.9%)	7.3% (1%)	2.2% (.5%)	7.1% (1%)	3.4% (.8%)		7.7% (1.0%)	2% (.5%)
300	5.2% (.7%)	2.3% (.6%)	5.9% (.9%)	2.3% (.7%)	4.2% (1.2%)	.9% (.5%)		5.4% (.7%)	2.4% (.7%)
900	4.5% (.7%)	4% (.7%)	5.4% (.8%)	3.4% (.6%)	4.6% (.8%)		1.9% (.4%)	5.5% (.8%)	2.7% (.8%)

Effects on the distribution of RT2

In addition, we conducted a Vincentized distribution analysis of RT2 to investigate the temporal dynamics of reward utilization in more detail. The procedure to compute the distribution analysis was identical to the procedure described for Experiment 1. Subsequently, the factors percentile, reward, SOA, and CTI were used in an ANOVA. With the aim of avoiding redundancy, we will report only the statistical parameters for effects that include the factor *percentile* for the previously indicated reason.

First, we obtained a significant three-way interaction of the factors reward, CTI, and percentile, $F(9, 207) = 2.50$, $p < 0.010$, $\eta_G^2 = 0.001$. As depicted in Fig. 7, the reward effects in the long CTI compared with the short CTI condition were increased. This effect was further specified as the

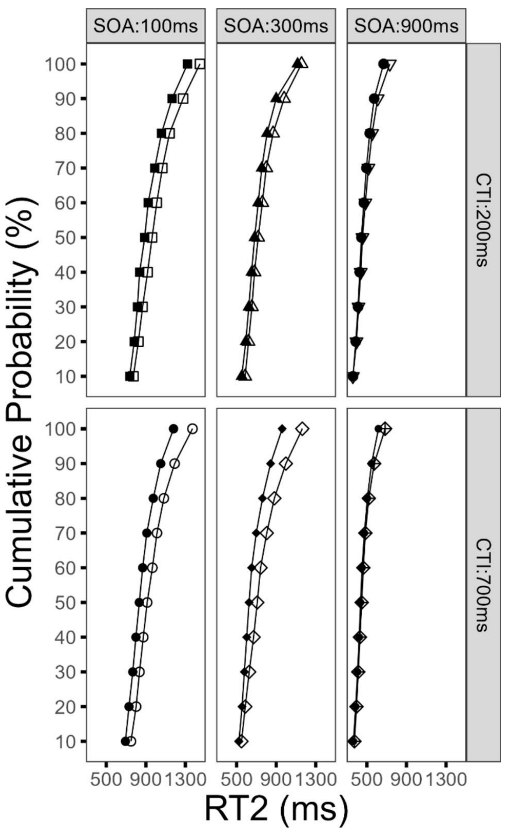

Fig. 7 Analysis of reaction time distribution for Task 2 (RT2) as a function of percentile, reward, stimulus-onset asynchrony (SOA), and cue–target interval (CTI) for Experiment 2. Filled symbols denote the reward condition. Empty symbols denote the no-reward condition

reward effects further increased, as RT2 got slower. In sum, this finding indicates that the reward effects increased with an increasing CTI, while longer RTs seemed to be especially susceptible to processing improvements.

Furthermore, the reward effects increased as RT2 increased. This observation was confirmed by a significant interaction of the factors reward and percentile on RT2, $F(9, 207) = 16.04$, $p < 0.001$, $\eta_G^2 = 0.003$. In addition, we obtained several further findings; the factor percentile reached significance, $F(9, 207) = 60.63$, $p < 0.001$, $\eta_G^2 = 0.278$. The interaction of the factors SOA and percentile also reached significance, $F(18, 414) = 60.00$, $p < 0.001$, $\eta_G^2 = 0.027$. In addition, we obtained a significant interaction of the factors percentile and CTI, $F(9, 207) = 5.52$, $p < 0.001$, $\eta_G^2 = 0.001$.

None of the following interactions reached significance: the interaction of the factors percentile, reward, and SOA did not reach significance, $F(18, 414) = 1.15$, $p = 0.305$, $\eta_G^2 < 0.001$. Similarly, the interaction of the factors percentile, CTI, and SOA was not significant, $F(18, 414) = 1.31$, $p = 0.174$, $\eta_G^2 < 0.001$. In addition, the four-way interaction of the factors percentile, reward, CTI, and SOA did not reach significance, $F(18, 414) = 1.34$, $p = 0.161$, $\eta_G^2 < 0.001$.

For the error rates on Task 2, only the interaction of the factors reward and SOA reached significance, $F(2, 46) = 3.36$, $p < 0.044$, $\eta_G^2 = 0.015$. Further tests indicated that there was a trend towards a slightly increased error rate for SOA 100, in the reward ($M = 3.3\%$) compared with the no-reward condition ($M = 2.1\%$), $t(23) = 1.88$, $p = 0.072$. This was not the case for the SOA 300 and SOA 900 conditions, as the descriptive data indicates a reduced error rate in the reward compared with the no-reward condition. As a result, the slightly increased error rate in the reward SOA 100 condition was accompanied by a reduced RT2; together these effects could suggest a dynamic adjustment of the response criteria of the participants.

Furthermore, the factor SOA did not reach significance, $F(2, 46) = 2.18$, $p = 0.125$, $\eta_G^2 = 0.015$. In addition, the interaction of the factors reward and CTI showed a trend, $F(1, 23) = 3.59$, $p = 0.071$, $\eta_G^2 = 0.005$. The main effect of the factor CTI did not reach significance, $F(1, 23) = 3.00$, $p = 0.097$, $\eta_G^2 = 0.004$. Also the interaction of the factors SOA and CTI did not reach significance, $F(2, 46) = 0.97$, $p = 0.385$, $\eta_p^2 = 0.007$. The main effect of the factor reward did not reach significance, $F(1, 23) = 0.04$, $p = 0.835$, $\eta_G^2 < 0.001$. In addition, the three-way interaction of the factors SOA, reward, and CTI did not reach significance, $F(2, 46) = 0.83$, $p = 0.442$, $\eta_G^2 = 0.002$.

Discussion

In Experiment 2, the trial-wise reward application for Task 1 performance resulted in a replication of the reward-related processing improvements from Experiment 1, as reflected by the main effect of reward on RT1 and RT2, and by the overadditive interaction of reward and SOA on RT2.

Importantly, the obtained results favor the assumption that the utilization of reward information improves with increasing CTI duration, as we obtained an overadditive interaction of reward and CTI on RT1 and RT2, with larger reward effects in the long CTI compared with the short CTI condition. This effect pattern was further specified by the results of a distribution analysis of RTs, indicating larger reward effects on longer RTs. Again, these reward-related processing improvements were accompanied by a main effect of CTI on RT1/RT2, reflecting improved task preparation. As a result, optimized task processing was further optimized by enhanced reward utilization, also for DT condition of increased temporal uncertainty. We will come back to this point in the general discussion part.

General discussion

The present study investigated whether participants can flexibly utilize trial-wise reward information to improve their DT performance. For this purpose, in Experiment 1, we applied a trial-wise reward application for participants' Task 1 performance in a PRP DT situation. We obtained an improved RT1 performance in the reward compared with the no-reward condition. Furthermore, we obtained an overadditive interaction of reward and SOA on RT2, with larger reward effects at short compared with long SOA. According to the effect propagation logic, such a reward pattern indicates that the prospect of reward affected the processing stages of Task 1 before or/at the bottleneck leading to a reduction of RT1. As a result, for the short SOA condition, the reward effect was propagated via the bottleneck mechanism onto Task 2, reducing RT2. In contrast for the long SOA condition, no bottleneck emerges between the tasks, thus no reward effect transmission could occur.

The second aim of Experiment 1 was to investigate the temporal dynamics of reward utilization. To this end, we combined a trial-wise reward prospect for Task 1 performance with a blocked CTI of either 200 ms or 700 ms. We obtained an overadditive interaction of reward and CTI on mean RT1 and RT2, with larger reward effects in the long compared with the short CTI condition. This reward pattern was further specified by the results of an RT distribution analysis, with larger reward effects on longer RTs in the long compared with the short CTI condition for RT1 and RT2. This finding suggests that the cognitive processing in trials with longer RTs is particularly susceptible to reward-CTI optimizations. In sum, these results are in line with the assumption that reward utilization is susceptible to the temporal duration of the CTI interval.

For Experiment 2, we investigated how temporal expectation affects the temporal dynamics of reward utilization by presenting varying CTIs randomly within blocks. We obtained an overadditive interaction of reward and CTI on mean RT1 and RT2, with larger reward effects in the long CTI compared with the short CTI condition. These results were further specified by the results of an RT distribution analysis on RT1 and RT2, indicating larger reward effects in the long CTI compared with the short CTI condition on longer RTs. Taken together the results favor the assumption that reward utilization improves with increasing duration of the CTI interval, for DT conditions of reduced temporal expectation.

Flexible utilization of reward information for behavioral adjustments in dual-task situations

The current study investigated whether participants can flexibly utilize reward information for performance improvements in DT situations. The results indicated that the prospect of reward rapidly improves mean Task 1 and Task 2 performance on a trial-to-trial basis, which suggests a flexible utilization of the reward information. In addition, the reward effects on the mean RT1/RT2 were further specified by larger reward effects on longer RTs, as indicated by the results of the RT1 and RT2 distribution analysis. Former studies reported that increased mental effort can lead to improved attentional mobilization which results in the stabilization of task performance, as was shown by the effect of mental effort on the right tail of the RT distribution (see also Steinborn et al., 2017). The current result pattern is therefore consistent with the assumption that the prospect of reward stabilized DT performance, by reducing the attentional fluctuation of DT performance in the reward compared with the no-reward condition. Furthermore, the current results indicate that substantial performance improvements are obtainable for DT conditions in which 50% of trials required the participants to utilize reward information for performance improvements. Consequently, these results extend previous studies in which a 20/80 proportion of effort and standard trials had been applied, indicating a large adaptivity of reward utilization of participants (see Kleinsorge, 2001; Steinborn et al., 2017; Strayer et al., 2024). Taken together, these results suggest that participants can rapidly utilize the reward information to improve and stabilize their DT performance.

Furthermore, the findings of a flexible utilization of reward information extend previous results with a block-wise reward application in DT situations. In particular, in previous investigations of our group, the application of reward prospect for Task 1 was implemented at the block level. For that purpose, participants were instructed that an entire block was rewarded and each trial was reward-relevant, which led to a constant prospect of reward across the whole rewarded blocks. As a result, participants could develop and apply a strategy of reward-induced preparation throughout the rewarded blocks to adjust their DT performance for obtaining a reward (Langsdorf et al., 2022). This resulted in reward effects on RT1 and larger reward effects at short compared with long SOA on RT2. This effect was interpreted with the effect propagation logic (Pashler, 1994; Schubert, 1999; Schweickert, 1980) indicating that the prospect of reward for Task 1 affected the processing stages of Task 1 before or/at the bottleneck, which was then transmitted via the bottleneck mechanism at short SOA onto the processing chain of Task 2, reducing RT2 as well. In contrast for the long SOA condition, the temporal overlap of the processing chain of Task 1 and Task 2 is reduced preventing the emergence of a bottleneck, thus leading to no effect propagation from Task 1 onto Task 2. In sum, the results of the trial-wise and block-wise reward application for Task 1 performance revealed similar reward effect patterns: the prospect of reward affects the pre-motoric processing stages of Task 1 improving RT1, leading to a transmission of the reward effects onto Task 2, resulting in larger reward effects for short compared with long SOA on RT2.

The pre-motoric locus of the reward effect would be in line with findings indicating that the prospect of reward enhances attentional allocation, stimulus processing, as well as attentional preparation. In particular, in a recent study applying electrophysiology with high temporal resolution, the effect of a cued reward prospect on conflict processing was investigated (Van Den Berg et al., 2014). The results indicated that the reward cue led to an enhancement of neural correlates of attentional allocation, stimulus processing, and attentional preparation. This was reflected by an enhanced amplitude of the N2 a component associated with the allocation of attention to salient stimuli, as well as an enhanced amplitude of the N1 a component associated with stimulus processing. Furthermore, the reward prospect boosted the amplitude of the contingent negative variation (CNV), an indicator of attentional preparation (Schevernels et al., 2014). Taken together, such effects of the reward prospect on neurophysiological components would be in line with our finding of a pre-motoric locus of the reward effect in the processing chain of Task 1 and Task 2.

Temporal dynamics of reward utilization in dual-task situations: On the relation of reward-related and preparation-related performance improvements

The second aim of the present study was to investigate the temporal dynamics of reward utilization. In particular, we were interested in whether the utilization of reward information is dependent upon the duration of the CTI. For Experiments 1 and 2, we obtained an overadditive interaction of reward and CTI on RT1 and RT2, reflecting larger reward effects in the long compared with the short CTI condition. Importantly, these effects were further specified by larger reward effects on longer RTs in the long CTI condition compared with the short CTI condition, as indicated by the results of the distribution analysis of RT1 and RT2. This effect pattern indicates that the prospect of reward builds up over time to improve the especially long RTs and that this optimization process is more effective at the long CTI condition compared with the short CTI condition. These results are consistent with the assumption that the utilization of reward information is susceptible to the length of the CTI interval. Taken together, the results show, to the best of our knowledge, a novel effect that provides useful insights into the temporal dynamics of reward processing.

Furthermore, these findings are relevant as there is an ongoing discussion on whether reward-related processing improvements reflect in essence preparation-related processing improvements (Capa et al., 2013; Kleinsorge & Rinkenauer, 2012; Rieger et al., 2021; Zedelius et al., 2012) or whether the prospect of reward leads to additional effects on task performance beyond preparation-related improvements. In particular, it had been reported and argued that the prospect of reward leads to improved preparation resulting in processing improvements as reflected by reduced RTs in the reward compared with the no-reward condition as well as to improved activation of ERP components associated with task-related preparation processes (Schevernels et al., 2014).

In contrast, the current findings suggest a different picture, as we observed an *overadditive* interaction of reward and CTI on DT performance, with larger reward-related processing benefits in the long CTI compared with the short CTI condition. As such, the obtained results indicate that even for optimal preparatory conditions as reflected by the improved RT1 and RT2 performance for the long compared with the short CTI condition, the prospect of reward *further* improved DT performance going beyond the preparation-related performance improvements. Such an effect pattern is not consistent with the assumption that the reward effects on the RTs reflect in essence preparation-related processing improvements (e.g., Rieger et al., 2021; Zedelius et al., 2012). But instead, these results favor the assumption that the prospect of reward elicited an additional effect on DT performance which goes beyond the temporal preparation effect. This inference is also in line with the results of the distribution analysis of RT1 and RT2 suggesting that especially trials with longer RTs profit most from the reward prospect in the long CTI condition. Taken together the results of Experiments 1 and 2 indicate that the prospect of reward can further improve DT performance even for optimal preparatory DT conditions.

An important further question is through which mechanism the overadditive reward-CTI interaction is emerging. One possibility could be that the prospect of reward and temporal preparation affect identical processes leading to the observed outcome. In particular, previous evidence by Seibold et al. (2011) demonstrated that conditions of high in contrast to low temporal preparation improved perceptual processing in a sensory-motor RT task by leading to an earlier onset of sensory information accumulation. When we consider the pre-motoric locus of the reward effect in the processing chain of Task 1 and Task 2 then it is conceivable that the prospect of reward improved processes related to the perception of Task 1. Similarly, for both experiments, the locus of the temporal preparation effect was pre-motoric, as reflected by the main effect of CTI on RT1 and the overadditive interaction of CTI and SOA on RT2, with larger CTI effects at short compared with long SOA on RT2. This finding is in line with previous evidence reporting a pre-motoric locus of the temporal preparation effect (Bausenhart et al., 2006, 2010; Seibold et al., 2011), that led to the specification that the temporal preparation effect impacts the onset of sensory information accumulation. Taken together, the loci of the reward effect and the temporal preparation effect are on pre-motoric processing stages in the processing chain of Task 1 and Task 2. As speculation, one could assume that this effect pattern indicates that both manipulations affected the onset of sensory information accumulation in an overadditive way. Such an assumption would be consistent with the observation that the prospect of reward can enhance auditory processing sensitivity in a sensory-motor RT task leading to improved task performance (Asutay & Västfjäll, 2016). In connection with the current results, the overadditive reward-CTI effects on RTs might result from a combined effect on the onset of sensory information accumulation. All in all, while it is conceivable that the prospect of reward and temporal preparation could jointly affect the onset of sensory information accumulation, further investigations are required to precisely establish the mechanism driving the novel overadditive reward-CTI effect.

A further aspect that should be discussed is whether the applied criteria for obtaining a reward may have affected the current result patterns.[3] Specifically, participants were instructed that fast and accurate Task 1 performance would be rewarded while the criterion applied for reward attainment was based on either RTs *or* error rates. In Experiment 1, this led to enhanced RT1/RT2 performance without differences in error rates between the reward and no-reward conditions. In Experiment 2, while RT1/RT2 performance was similarly enhanced, there was a slight tendency for increased Task 2 error rates in the reward compared with the no-reward condition for the SOA 100 task situation. These results indicate that our reward criterion instruction for obtaining a reward did not lead to a systematic prioritization of speed over accuracy by the participants.

This conclusion is further corroborated by previous results of our group, in which the same criteria for obtaining a reward led to improved RT1/RT2 processing *and* reduced error rates in the reward compared with the no-reward condition (Langsdorf et al., 2025). In sum, combined evidence suggests that our applied criteria for reward attainment reliably improves processing speed, while varying effects on the error rates can occur (see also Falkenstein et al., 2003; Kleinsorge, 2001). Future studies might systematically investigate how varying criteria for reward attainment affect RTs and error rates for varying task conditions.

Reward utilization in dual-task situations with reduced temporal expectation

A further relevant aspect was whether temporal expectation affected the utilization of reward information in Experiment 1 as we applied blocked CTIs for which participants could develop a precise temporal expectation of Task 1 onset. This task setup led to an overadditve interaction of reward and CTI on RT1 and RT2, reflecting larger reward effects in the long compared with the short CTI condition. In contrast, for Experiment 2, we applied randomized CTIs for which participants could not develop a precise temporal expectation of Task 1 onset. For this case, temporal uncertainty emerged as it was not evident at the start of the trial which CTI would be presented to the participants. The obtained results indicated that for DT conditions with temporal uncertainty, the reward effects in the long CTI were increased compared with the short CTI condition for RT1 and RT2. This indicates that the utilization of reward information improved for longer preparation durations, also under conditions of less predictable DT situations.

However, it has to be noted that the application of the randomized CTIs from Experiment 2 still enables the participants to establish a temporal expectation of Task 1 onset. As the CTIs were not drawn from a nonaging but from an aging distribution, the conditional probability of Task 1 onset increased with increasing CTI length (Fischer et al., 2007). Based upon that participants may utilize this information to estimate Task 1 onset to strategically prepare for Task 1 processing. Future studies could further control for such strategical preparation effects by drawing the CTIs from a nonaging distribution to explore the boundary conditions for the reward–CTI interaction.

[3] We thank an anonymous reviewer for pointing out that criteria for reward attainment might be linked to dynamic adjustments of response criteria of participants, which emerge as speed–accuracy trade-off effects, in reward compared with no-reward conditions.

Current directions in the investigation of reward-related processing improvements in sensory-motor RT tasks

The present investigation aligns with several other studies that explored reward-related processing improvements (Chiew & Braver, 2016; Falkenstein et al., 2003; Fischer et al., 2018; Kleinsorge, 2001; Kleinsorge & Rinkenauer, 2012; Kool & Botvinick, 2018; Langsdorf et al., 2022, 2025; Rieger et al., 2021; Steinborn et al., 2017). In most of these studies, it was assumed that the prospect of reward ramps up task-related preparatory processes, leading to improved task performance. However, accumulating evidence suggests that the prospect of reward could stimulate additional optimization processes.

A further relevant line of research provided evidence consistent with the assumption that the prospect of reward can modulate the flexibility-stability balance of cognitive control (Shen & Chun, 2011; see also Fröber & Dreisbach, 2014, 2016; Fröber et al., 2019). To investigate this, the authors applied the task-switching methodology, in which participants switch (change task compared with previous trial) or repeat (repeat task compared with previous trial) between two sensory-motor RT tasks. This typically leads to longer RTs for the switch compared with the repetition condition, and the resultant switch costs (i.e., switch–repeat RTs) are considered as an indicator of cognitive flexibility. The authors reported that a constant reward prospect from trial $n-1$ to trial n, in contrast to an increasing reward prospect, increases the switch costs. This result pattern emerges for the reward remain condition compared with the reward increase condition, since the repetition trial RTs decrease while switch trial RTs increase. These findings are consistent with the assumption that the constant reward prospect leads to a stabilization of the task representation, resulting in maximized processing speed, while cognitive flexibility is reduced. Taken together, the authors suggest that the prospect of reward can activate a stable as well as a flexible mode of cognitive control, leading to the regulation of information processing policies.

Related to the current case, it is an open issue how DT processing is modulated by the reward history classification (constant vs. increasing reward prospect) as applied by Fröber and Dreisbach (2016; see also Shen & Chun, 2011). To investigate this, we classified trials as either a reward remain trial or a reward increase trial based on whether the reward prospect remained constant or increased from trial $n-1$ to trial n.

The results showed that RT1 was faster in the reward remain condition compared with the reward increase condition (see statistical details here[4]). This result pattern indicates that the constant reward prospect leads to a similar effect of reward-related optimization on DT and task-switching performance (i.e., maximizing processing speed). Related to the flexibility-stability framework, this result pattern could reflect an increased stability of the task representation (i.e., goal maintenance) induced by the constant reward prospect *and* the instruction to mobilize mental effort. Future studies should investigate whether the prospect of reward can also improve cognitive flexibility during DT situations. In this context, it could be worthwhile to investigate whether the prospect of reward can improve cognitive flexibility for the coordination of two tasks as required in DT situations with a variable task order (Schubert, 2008).

Conclusion

We provided evidence for the assumption that participants can flexibly utilize a trial-wise reward prospect for their Task 1 performance resulting in rapid improvement and stabilization of DT performance. Furthermore, we obtained evidence that well-prepared DT processing was further improved by reward utilization with an increasing CTI, favoring the assumption that the prospect of reward elicited additional processing improvements going beyond the preparation-related processing improvements. Taken together, we provided novel evidence on the temporal dynamics of reward utilization in DT situations.

[4] As suggested by an anonymous reviewer, we conducted an exploratory analysis of how the reward history and CTI affect RT1. For Experiment 1, we obtained a main effect of reward history, $F(1, 24) = 15.19$, $p < .001$, $\eta_G^2 = .060$, with a shorter RT1 in the reward remain compared with the reward increase condition. Furthermore, we obtained a main effect of CTI, $F(1, 24) = 17.75$, $p < .001$, $\eta_G^2 = .046$, with a reduced RT1 in the long compared with the short CTI condition. Finally, the interaction of the factors reward history and CTI did not reach significance. For Experiment 2, we obtained a main effect of reward history, $F(1, 23) = 13.99$, $p < .001$, $\eta_G^2 = .042$, with a reduced RT1 in the reward remain compared with the reward increase condition. Furthermore, we obtained a main effect of CTI, $F(1, 23) = 12.37$, $p < .002$, $\eta_G^2 = .011$, with a shorter RT1 in the long compared with the short CTI condition. Finally, the interaction of the factors reward history and CTI, reached significance, $F(1, 23) = 6.28$, $p < .020$, $\eta_G^2 = .004$. The CTI effect (short minus long CTI) was increased in the reward remain ($M = 52$ ms) compared with the reward increase ($M = 13$ ms) condition. Consequently, this pattern of results indicates that a) RT1 processing profited most when the reward prospect remained constant and b) that participants required two consecutive reward-related trials to optimize their task processing, for task conditions of reduced temporal expectation.

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Programming experiment: L.L.
Data analysis: L.L. and T.S.
Writing: L.L. and T.S.

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Data availability The data generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability Analysis scripts are available from the corresponding author on reasonable request.

Declarations

Ethics approval The study was conducted according to the criteria set by the declaration of Helsinki.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication All participants provided written informed consent for the publication of their data and the study results.

Conflict of interest The authors report no conflict of interest.

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18. German Summary

In den letzten Dekaden wurden die Mechanismen der menschlichen Informationsverarbeitung umfassend untersucht. Ein neuer Fokus ist die Frage, wie motivationale Anreize die Informationsverarbeitung beeinflussen. Für die Doppelaufgaben (DA) Situation, also in Aufgabensituationen mit zwei Aufgaben, gibt es bisher nur wenig Evidenz wie die Performanz durch motivationale Anreize moduliert wird. Die vorliegende Dissertation geht der Frage nach, welchen Einfluss Motivation in Form von monetärem Anreiz auf die kognitive Verarbeitung in DA Situationen ausübt. Diese Frage wurde mittels des psychologischen Refraktär Perioden (PRP) Paradigmas untersucht, wobei chronometrische Methoden angewendet wurden. Diese Methoden ermöglichen es, den Lokus (die Lokalisation) des Belohnungseffektes in der Verarbeitungskette von PRP DA Situationen zu analysieren.

Vor den Kapiteln findet man das Abstract, die Liste der Artikel, sowie die Danksagung.

In **Kapitel 4** wird ein konzeptueller Rahmen für die vorliegende Dissertation geliefert. Dieser umfasst eine Einführung der allgemeinen Forschungsfrage: Welche kognitiven Prozesse werden von monetärer Belohnung in DA Situationen beeinflusst? Führt eine belohnungs-basierte Verarbeitungsverbesserung in einer Aufgabe auch zu einer Verbesserung in der anderen Aufgabe? Sind Personen in der Lage ihren Belohnungsverarbeitungsmodus flexibel zu wechseln? Was sind die Grundlagen der belohnungsbasierten Performanzverbesserung? Diese vier Probleme werden in der vorliegenden Dissertation untersucht.

In **Kapitel 5** wird das PRP-Paradigma vorgestellt, welches in dieser Arbeit verwendet wurde. Im PRP-Paradigma werden zwei diskrete sensorisch-motorische Reaktionszeit (RZ) Aufgaben kombiniert, welche durch ein variables zeitliches Intervall getrennt sind, die Stimulus-Onset Asynchronie (SOA). Das führt dazu, dass die RZ der zweiten Aufgabe (RZ2; Aufgabe 2) mit abnehmender SOA zunimmt, wohingegen die RZ der ersten Aufgabe (RZ1; Aufgabe 1) von der zeitlichen Überlappung unbeeinflusst ist. Der PRP-Effekt beschreibt die längere RZ2 bei kurzem im Vergleich zu langem SOA.

Dieser Effekt kann durch das zentrale Bottleneck Modell erklärt werden. Dieses nimmt an, dass beide Aufgaben in diskrete Verarbeitungsstufen unterteilt werden können, welche erst verarbeitet werden können, wenn die vorherige Stufe vollständig verarbeitet wurde. Die Verarbeitungsstufen sind die perzeptive Stufe (hier wird die perzeptive Analyse des Stimulus durchgeführt), die Antwortauswahl (hier wird die perzeptive Information an die notwendige Antwort gebunden) und die motorische Stufe, welche die motorische Reaktion initiiert. Zusätzlich nimmt das Modell an, dass die perzeptiven und motorischen Prozesse parallel ablaufen können, wohingegen die Antwortauswahlen der beiden Aufgaben seriell ablaufen. Das Modell erklärt den PRP-Effekt damit, dass bei kurzem SOA die Verarbeitungsketten von Aufgabe 1 und 2 zeitlich überlappen, was dazu führt, dass die Antwortauswahl seriell ausgeführt werden muss. Im Gegensatz zu längeren SOAs, hier ist die zeitliche Überlappung der Prozesse reduziert, was zu einer Verringerung der RZ2 führt. Dieses Befundmuster führte zu der Schlussfolgerung, dass die Antwortauswahl kapazitätslimitiert ist und damit der Bottleneck zu einer seriellen Ausführung beider Antwortauswahlstufen von Aufgabe 1 und 2 führt. Grundsätzlich wird für die Untersuchung der Frage, wie monetärer Anreiz DA Performanz beeinflusst, auf die theoretischen Annahmen des zentralen Bottleneck Modells zurückgegriffen.

In **Kapitel 6**, wird das Paradigma des Monetary-Incentive Delay (MID) Task vorgestellt, welches dazu verwendet wird, Belohnungs-Kognition Interaktionen zu untersuchen, so auch in der vorliegenden Dissertation. Dieses Paradigma kann entweder pro Trial oder Block angewendet werden, um Strategien der Belohnungsverarbeitung zu untersuchen. In beiden Fällen wird den Probanden vorab ein Hinweisreiz präsentiert, welcher anzeigt, ob eine Belohnung verdient werden kann oder nicht; in der Folge wird die Performanz dem Belohnungsplan entsprechend belohnt. In der Regel erhalten die Probanden ein Feedback über ihre Leistung wie z.B. die RZ, Fehlerraten und die verdiente Belohnung. Frühere Evidenz konnte zeigen, dass die RZ in belohnten im Vergleich zu unbelohnten Durchgängen verkürzt sind. In der Folge wird in Kapitel 6 der derzeitige Wissensstand über die physiologischen Grundlagen der RZ-Verbesserungen dargestellt.

In **Kapitel 7** wird die frühere Evidenz zu belohnungsbasierten Verbesserungseffekten in sensorisch-motorischen RZ-Aufgaben dargestellt. Frühere Ergebnisse aus DA Studien lieferten hierzu unklar Ergebnisse. Zusätzlich dazu zeigt die Evidenz aus Einzelaufgabensituationen, dass es zu spezifischen Effekten der monetären Belohnung auf kognitive Prozessstufen kommt. Daher wird Evidenz aus Einzelaufgabensituationen diskutiert, bei der die Aussicht auf Belohnung zu einer Verbesserung von perzeptiven Prozessen, der Antwortauswahl oder motorischen Prozessen geführt hat. Die Ausführung schließt damit, dass in einer DA Situation jede dieser Prozessstufen betroffen sein könnte und damit der Lokus des Belohnungseffekts in PRP DT Situationen ein offenes Problem ist.

Der zweite Fragenkomplex, der behandelt wird, diskutiert die Frage, ob es zu belohnungsbasierten Übertragungseffekten zwischen Aufgaben in DA Situationen kommt. Bisher gibt es dazu unklare Ergebnisse, welche die Frage offenlassen, ob es tatsächlich zu einer Übertragung der Belohnungseffekte kommt. In der Folge sollen die DA Situationen untersucht werden, in denen es zu belohnungsbasierten Übertragungseffekten zwischen den Aufgaben kommt. Die beiden ausgeführten Fragestellungen beziehen sich auf Studie 1 und Studie 2.

In **Kapitel 8** wird erläutert, dass bisher ausschließlich Block-basierte Belohnung in DA Situationen angewendet wurde. Das bedeutet, dass es unklar ist, ob Versuchspersonen in der Lage sind, ihre Belohnungsverarbeitung auf eine Trial-basierte Belohnung umzustellen. In der Folge wird Evidenz zu dieser Problemstellung vorgestellt. Konkret wird dargestellt, dass im Fall der Trial-basierten Applikation die Probanden von Trial zu Trial ihre Verarbeitungsstrategie anpassen müssen, um eine Belohnung zu erhalten; im Gegenteil zu einer Block-basierten Anwendung, bei der die Probanden einen Verarbeitungsmodus für einen ganzen Belohnungsblock anwenden können. Damit unterscheiden sich die Verarbeitungsstrategien für die beiden Arten der Belohnungs-Applikation, wobei für beide Applikationen Verbesserungen der Leistung festgestellt wurden.

In **Kapitel 9** wird die aktuelle Diskussion um die Grundlage der Belohnungs-basierten Verbesserungseffekte erläutert und aufgezeigt, dass die meisten Autoren davon ausgehen, dass Belohnung die vorbereitenden Prozesse verbessert. Wobei es gleichzeitig so ist, dass unzureichende Evidenz über das Verhältnis von Belohnungseffekten und Preparationseffekten vorliegt. In der Folge wird daher in diesem Kapitel die Methodik zur Untersuchung von Vorbereitungseffekten vorgestellt, welche verwendet wurde, um den gemeinsamen Effekt von Belohnung und Vorbereitung zu untersuchen.

Daraufhin wird die Evidenz dargestellt, welche zeigen konnte, dass die zeitliche Dynamik bei der Verwendung von Belohnungsinformation eine Rolle spielt. In einer Studie haben Chiew und Braver (2016) zeigen können, dass eine Belohnungsinformation und eine Vorabinformation über die Kongruenz/Inkongruenz der folgenden Aufgabensituation die Interferenzkontrolle in einer Erikson-Flanker Aufgabe nur bei langer Vorbereitungszeit überadditiv verbessern konnte. Dieser Befund legt damit nahe, dass es einen Zusammenhang zwischen den zeitlichen Bedingungen in einem Trial und der Nutzbarkeit von Belohnungsinformation gibt.

In **Kapitel 10** werden die Forschungsfragen für Studie 1-3 abgeleitet und dargestellt. Für Studie 1 wurden Probanden nur für ihre Leistung in Aufgabe 1 belohnt. In der Folge soll der Lokus des Belohnungseffektes in der Verarbeitungskette von Aufgabe 1 und 2 analysiert werden. Um dies zu tun, werden chronometrische Methoden angewendet, die im Methodenteil von Studie 1 beschrieben werden.

Für Studie 2 wurden die Probanden nur für ihre Leistung in Aufgabe 2 belohnt. Damit wurde die Aufgabe belohnt, für welche die Verarbeitungskette von einem Bottleneck unterbrochen wird. Damit ergibt sich die Frage, welchen Einfluss das auf die PRP DT Performanz hat. Zur Untersuchung dieser Fragestellung werden chronometrische Methoden verwendet, die im Kapitel zu Studie 2 vorgestellt werden.

In Studie 3 wurde untersucht, ob Probanden ihren Belohnungsverarbeitungsmodus flexibel zwischen den Trials wechseln können, um ihre DT Performanz zu verbessern. Dabei wurde auf die Ergebnisse aus Studie 1 und 2 zurückgegriffen, um die RZ-Vorhersagen zu formulieren, die mittels chronometrischer Methoden interpretiert wurden. Als weitere Forschungsfrage wurde die zeitliche Dynamik der Belohnungsverwendung untersucht. Zu diesem Zweck wurden unterschiedlich lange Vorbereitungsintervalle mit einer Belohnung für die Leistung in Aufgabe 1 kombiniert. In der Folge wurde der kombinierte Effekt auf die Performanz von Aufgabe 1 und 2 analysiert.

In **Kapitel 11** werden die Ergebnisse von Studie 1 zusammengefasst. Zur Darstellung der Studie werden zunächst unterschiedliche Loci des Belohnungseffekts in der Verarbeitungskette von Aufgabe 1 vorgestellt, welche mit unterschiedlichen RZ1 und RZ2 Mustern einhergehen. Diese RZ-Muster sind mittels chronometrischer Methoden wie der Effekt-Propagation Methode, als auch der Locus-of-Slack Methode analysierbar.

Die Ergebnisse von Experiment 1 zeigten, dass die Belohnung für Aufgabe 1 zu einer Verkürzung der Prozessstufen vor und/oder während des Bottlenecks geführt haben, was zu einer Reduktion der RZ1 in der belohnten im Vergleich zur unbelohnten Bedingung geführt hat. Dieser Belohnungseffekt wurde dann über den Bottleneck auf Aufgabe 2 propagiert, was die RZ2 ebenfalls verkürzte und zu größeren Belohnungseffekten bei kurzem im Vergleich zu langem SOA führte. Zusätzlich führte die Belohnung für Aufgabe 1 dazu, dass die motorischen Prozesse von Aufgabe 1 verkürzt wurden.

In Experiment 2 wurde untersucht, welche Prozessstufe von Aufgabe 2 durch die Belohnung von Aufgabe 1 früher verarbeitet wurde. Zu diesem Zweck wurde der Bottleneck in der Verarbeitungskette von Aufgabe 1 und 2 lokalisiert. Dafür wurde die Schwierigkeit der Antwortauswahl von Aufgabe 2 variiert, was in einer leichten und schwierigen Aufgabensituation resultierte. Um nun festzustellen, ob der Bottleneck an der Antwortauswahlstufe oder der motorischen Stufe entsteht, muss das RZ2 Muster analysiert werden.

Für Experiment 2 zeigte sich, dass die RZ2 in der schwierigen Bedingung verlängert war, und zwar bei kurzem und langem SOA. Dieses Muster tritt ein, wenn die zusätzliche Verarbeitungsdauer in der schwierigen Bedingung nach dem zentralen Bottleneck angehängt wird und damit die RZ2 verlängert. Das führt zu der Schlussfolgerung, dass ein Bottleneck an den zentralen Stufen der Antwortauswahl vorliegt. Für die Propagation des

Belohnungseffektes bedeutet das, dass die Antwortauswahl in der belohnten Bedingung von Aufgabe 2 früher verarbeitet wurde. In der Folge werden zum Ende des Kapitels Implikationen der Resultate diskutiert.

In **Kapitel 12** werden die Ergebnisse von Studie 2 dargestellt. Die Darstellung umfasst zunächst die unterschiedlichen Loci des Belohnungseffektes, wenn die Belohnung für Aufgabe 2 die Verarbeitung von Aufgabe 2 verbessert. Diese möglichen RZ-Muster werden mittels der Locus-of-Slack Methode interpretiert. Zusätzlich dazu werden die möglichen Loci des Belohnungseffektes auf Aufgabe 1 mithilfe der Effekt-Propagation Methode diskutiert.

Die Ergebnisse von Experiment 1 zeigten, dass die Belohnung für Aufgabe 2 zu einer Verbesserung in der Leistung von Aufgabe 1 führt. Hierbei wurden die Prozesse vor oder während des Bottlenecks von Aufgabe 1 verbessert, was zu einem Belohnungseffekt auf Aufgabe 1 führt. In der Folge wurde die Verkürzung der Verarbeitungsdauer über den Bottleneck auf Aufgabe 2 übertragen. Das resultiert in größeren Belohnungseffekten bei kurzem im Vergleich zu langem SOA auf die RZ2.

Für Experiment 2 wird die Annahme des zentralen Bottlenecks von Experiment 1 überprüft, um festzustellen über welche Stufe der Belohnungseffekt von Aufgabe 1 auf Aufgabe 2 propagiert. Zu diesem Zweck wurde die Schwierigkeit von Aufgabe 2 variiert, resultierend in einer leichten und einer schwierigen Bedingung. In der Folge ermöglichte Analyse von RZ2 die Schlussfolgerung, ob der Belohnungseffekt über die Antwortauswahl oder die Motorstufe von Aufgabe 1 auf Aufgabe 2 propagierten.

Die Ergebnisse von Experiment 2 zeigten, dass die RZ2 in der schwierigen Bedingung bei kurzem und langem SOA verlängert war. Dieses RZ2 Muster zeigt an, dass die zusätzliche Verarbeitungsdauer nach dem zentralen Bottleneck hinzuaddiert wurde.

Daraus kann geschlossen werden, dass der Belohnungseffekt von Aufgabe 1 auf die Antwortauswahl von Aufgabe 2 propagiert ist. Zum Ende des Kapitels werden Implikationen der Resultate diskutiert.

In **Kapitel 13** werden die Ergebnisse von Studie 3 dargestellt. Die Darstellung umfasst die Ableitung der Hypothesen für Forschungsfrage 1, ob Probanden in der Lage sind, flexibel Belohnungsinformation zu nutzen, um ihre DA Performanz zu verbessern. Hierfür wird sich auf die vorherigen Ergebnisse aus Studie 1 und 2 bezogen und ein erwartetes RZ-Muster vorhergesagt, welches mittels der Effekt-Propagation Methode interpretiert wird. Daraufhin wird das Hypothesenpaar für die zweite Forschungsfrage formuliert. Hierbei geht es im Kern um die Frage, ob der Belohnungseffekt auf RZ1 schon bei einem kurzen Vorbereitungsintervall sein Maximum erreicht hat, oder ob der Belohnungseffekt mit zunehmender Dauer des Vorbereitungsintervalls zunimmt.

Die Ergebnisse von Experiment 1 zeigen, dass die Probanden in der Lage sind, die Belohnungsinformation flexibel zu nutzen. Außerdem hat die Belohnung für Aufgabe 1 die Prozessstufen vor oder während des Bottlenecks verkürzt, was zu einer verkürzten RZ1 führt. In der Folge führt das zu einer Übertragung des Belohnungseffektes auf Aufgabe 2. Damit entstehen größere Belohnungseffekte bei kurzem im Vergleich zu langem SOA auf RZ2.

Außerdem werden größere Belohnungseffekte bei einem langen Vorbereitungsintervall als bei einem kurzen Vorbereitungsintervall auf die RZ1 und RZ2 gefunden. Diese Effekte werden zusätzlich durch eine Untersuchung der RZ-Verteilung bestärkt. Dort lassen sich größere Effekte auf längere RZ finden. Diese Ergebnismuster lassen den Schluss zu, dass die Nutzung von Belohnungsinformation mit zunehmendem Vorbereitungsintervall optimiert wird und dass vor allem längere RZ davon profitieren.

Für Experiment 2 wurde die Darbietung der Vorbereitungsintervalle randomisiert, damit ist im Gegensatz zu Experiment 1 keine exakte Vorbereitung auf die Präsentation des ersten Stimulus mehr möglich. Die Ergebnisse von Experiment 2 replizieren die Ergebnisse von Experiment 1 und belegen damit, dass ein längeres Vorbereitungsintervall die Nutzung von Belohnungsinformation optimiert und das sowohl für DA Situationen, die vorhersagbar als auch weniger vorhersagbar sind. Zum Ende des Kapitels werden Implikationen der Resultate diskutiert.

In **Kapitel 14** werden die Hauptergebnisse der Studien 1-3 zunächst zusammengefasst und dann diskutiert. Das Kapitel schließt damit, dass experimentelle Fortführungen skizziert werden und eine Schlussfolgerung über die Ergebnisse der Dissertation gezogen wird.

Für **Studie 1** konnte gezeigt werden, dass die Belohnung für Aufgabe 1 zu einer Verbesserung der kognitiven Prozesse geführt hat. Hier werden nun die aktuellen Resultate mit vorherigen Ergebnissen in Bezug gesetzt. Konkret ist es so, dass die Belohnung sowohl perzeptive Prozesse und/oder Prozesse der Antwortauswahl verbessert haben kann. In Kombination mit dem Ergebnis, dass auch motorische Prozesse verbessert wurden, erweitern diese Ergebnisse vorherige Ergebnisse aus Einzelaufgaben Situationen. Zusätzlich dazu wird beschrieben, dass mit Hilfe von Studie 1, die DA Situationen aufgezeigt wurden, in denen es zu einer Propagation des Belohnungseffektes auf Aufgabe 2 kam. Dieses Ergebnis erweitert bisherige Ergebnisse, welche keine belohnungsbasierten Verbesserungen der Aufgaben 2 Performanz nachweisen konnten.

Weiterhin wird beschrieben, dass die Ergebnisse von Studie 1 darlegen, dass die Applikation von Belohnung zu keiner parallelen Verarbeitung der Antwortauswahl von Aufgabe 1 und 2 geführt hat. Diese Möglichkeit würde aber unter der Annahme eines strategischen Bottlenecks bestehen. Die Belohnungserwartung hätte dazu führen können, dass die Probanden in einen risikoreicheren Verarbeitungsmodus übergehen. In der Folge hätte eine parallele Verarbeitung der beiden Prozessstufen entstehen können. Die Ergebnisse von Studie 1 belegen jedoch, dass dies nicht der Fall gewesen ist.

Für **Studie 2** konnte gezeigt werden, dass die Probanden die Belohnung für Aufgabe 2 auf Aufgabe 1 bezogen haben. In der Folge kam es zu einer Stufenverkürzung der perzeptiven und/oder der Antwortauswahl von Aufgabe 1. Dieser Belohnungseffekt wurde über den Bottleneck auf Aufgabe 2 übertragen, was zu einer Leistungsverbesserung in Aufgabe 2 geführt hat, wobei diese größer bei kurzem im Vergleich zum langen SOA ausgefallen ist.

Im Weiteren wird eine Möglichkeit erläutert, weshalb es zu einer Leistungsverbesserung in Aufgabe 1 gekommen ist. Hierbei wird auf die Evidenz aus Studien verwiesen, die zeigen konnten, dass Probanden eine DA Situation nicht als zwei getrennte Aufgabenketten repräsentieren, sondern dass die Probanden eine DA Repräsentation vor dem Start des Trials aktivieren, die die Verarbeitungssequenz von Aufgabe 1 und Aufgabe 2 reguliert. In der Folge könnten Probanden die Belohnung für Aufgabe 2 auf die gesamte DA Repräsentation bezogen haben und da ein Trial immer mit Aufgabe 1 startet, führte das zu einer Verbesserung der Leistung in Aufgabe 1.

Darüber hinaus werden die Ergebnisse von Studie 1 und Studie 2 gemeinsam im Hinblick auf die Frage der Übertragungseffekte zwischen Aufgabe 1 und Aufgabe 2 diskutiert. Hier kann nun angeführt werden, dass die Übertragungseffekte zwischen den Aufgaben besonders dann stattfinden, wenn die zeitliche Überlappung zwischen Aufgabe 1 und Aufgabe 2 besonders groß ist, also bei kurzem SOA. Da es bisher divergierende Ergebnisse hinsichtlich der Übertragungseffekte auf Aufgabe 2 gab, werden die Ergebnisse zu den

Ergebnissen von Rieger et al. (2021) in Bezug gesetzt.

Die Diskussion der Ergebnisse von Studie 2 schließt damit, dass die Evidenz von Studie 1 und 2 hinsichtlich der größeren Rewardeffekte auf die belohnte Aufgabe im Vergleich zur unbelohnten Aufgabe, den Schluss nahelegen, dass die Versuchspersonen beiden Aufgaben einen unterschiedlichen Wert zu gewiesen haben könnten. In der Folge kam es dann zu einer unterschiedlichen Allokation von Verarbeitungskapazitäten für die belohnte und unbelohnte Aufgabe.

Für **Studie 3** konnte gezeigt werden, dass Probanden in der Lage sind, Belohnungsinformation flexibel zu nutzen, um ihre DA Leistung zu verbessern. Weiterhin konnte gezeigt werden, dass die Belohnungseffekte mit zunehmendem Vorbereitungsintervall größer wurden, sowohl für vorhersagbare DA als auch für weniger vorhersagbare DA Situationen.

Daraufhin werden die Implikationen der Befunde diskutiert. Hierbei wird darauf hingewiesen, dass obwohl sich die Leistung der Probanden aufgrund der längeren Vorbereitungsintervalle verbesserte hatte, im Vergleich zu den kurzen Vorbereitungsintervallen, es weiterhin zu einer belohnungsbasierten Verbesserung der Leistung kam. Dieser Befund wird mit der aktuellen Debatte über das Verhältnis von belohnungsbasierter und vorbereitungsbasierter Leistungsverbesserung in Zusammenhang gebracht. Hierbei wird betont, dass die Ergebnisse einen zusätzlichen Verbesserungseffekt durch die Belohnungserwartung anzeigen, welcher über einen reinen Vorbereitungseffekt hinausgeht.

Das Kapitel schließt mit der Skizzierung zukünftiger Experimente. Hierbei werden Möglichkeiten für weitere Lokalisations-Studien aufgezeigt, welche sich chronophysiologischer Methoden bedienen. Außerdem werden Experimente skizziert, die darauf abzielen die zeitliche Dynamik der Belohnungsnutzung weiter zu untersuchen.

19. Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die Arbeit selbstständig und ohne fremde Hilfe verfasst, keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

Unterschrift des Antragstellers

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