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ORIGINAL ARTICLE

Investigating limits of task prioritization in dual-tasking: evidence from the prioritized processing and the psychological refractory period paradigms

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Abstract

Dual-tasking often requires prioritizing one task over the other. For example, in the psychological refractory period (PRP) paradigm, participants are instructed to initially respond to Task 1 (T1) and only then to Task 2 (T2). Furthermore, in the prioritized processing paradigm (PP), participants are instructed to perform T2 only if T1 was a no-go trial—requiring even more prioritization. The present study investigated the limits of task prioritization. Two experiments compared performance in the PRP paradigm and the PP paradigm. To manipulate task prioritization, tasks were rewarded differently (e.g., high reward for T1, low reward for T2, and vice versa). We hypothesized (a) that performance will improve for the highly rewarded task (Experiments 1 and 2) and (b) that there are stronger reward effects for T1 in the PRP than in the PP paradigm (Experiment 2). Results showed an influence of reward on task prioritization: For T1, high reward (compared to low reward) caused a speed-up of responses that did not differ between the two paradigms. However, for T2, reward influenced response speed selectively in the PP paradigm, but not in the PRP paradigm. Based on paradigm-specific response demands, we propose that the coordination of two motor responses plays a crucial role in prioritizing tasks and might limit the flexibility of the allocation of preparatory capacity.

Introduction

When working on two tasks simultaneously (i.e., dual-tasking), performance often suffers compared to a single-task situation (e.g., Pashler 1994; Tombu & Jolicœur, 2004). This finding shows that our cognitive system underlies fundamental limitations when required to deal with multiple tasks at the same time. For instance, when driving a car, driving performance is impaired when performing another task at the same time (Levy & Pashler, 2008). To minimize performance decrements of the focal task, one needs to prioritize tasks (Levy & Pashler, 2008, see also Schuch, Dignath, Steinhauser, & Janczyk, 2019).

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In a laboratory setting, dual-tasking is often studied using the psychological refractory period (PRP) paradigm (Pashler, 1994; Telford, 1931; Welford, 1952). In the PRP paradigm, participants are required to respond to two stimuli (S1 and S2) of two tasks (T1 and T2) in rapid succession. For example, participants are asked to first perform a letter task by classifying one of the two letters with their index fingers (i.e., press right/left, T1) and then to perform a color task by classifying one of the two colors of a colored square around the letter with their middle fingers (i.e., press right/left, T2). Please note that in the current experiments, we used a variant of the PRP paradigm, by adding no-go stimuli to both tasks for better comparability with the prioritized processing (PP) paradigm, which is described later below (Miller & Durst, 2014).

In the PRP paradigm, the two stimuli are presented with a stimulus onset asynchrony (SOA) and the reaction times of the two discrete responses (RT1 and RT2) are used as the critical performance measure. Two observations are of particular relevance: First, RT2 decreases linearly with increasing SOA between S1 and S2—the typical PRP effect (e.g., Meyer & Kieras, 1997a, b; Navon & Miller, 2002; Pashler, 1994; Tombu & Jolicoeur, 2002). Second,

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RT1 is slower in the PRP paradigms' dual-task setting than in a single-task setting (Pashler, 1994; Schumacher et al., 2001; Tombu & Jolicœur, 2004). An explanation for the second finding is differences in task preparation (e.g., De Jong, 1995; De Jong & Sweet, 1994; Gottsdanker, 1980; Navon & Miller, 2002; Schubert, 1999). Task preparation results in more efficient processing presumably at one or more processing stages (i.e., perception, response selection, and motor execution). Consequently, increased preparation results in faster responses (e.g., Meiran, 2000). When performing two or more tasks, task preparation is limited—presumably because restricted working memory capacity needs to be shared to maintain multiple task sets active (e.g., Lien, Schweickert, & Proctor, 2003; Poljac, Koch, & Bekkering, 2008). Thus, more preparation for T1 automatically leads to less preparation for T2 and vice versa (e.g., Gottsdanker, 1980; Maslovat et al., 2013; Navon & Miller, 2002).

Interestingly, findings from another dual-task paradigm (i.e., the prioritized processing (PP) paradigm, Miller, 2017; Miller & Durst, 2014, 2015; Mittelstädt & Miller, 2017) suggest that people are able to adapt to different task requirements. The PP paradigm places more emphasis on T1. Specifically, no-go stimuli are added to both tasks (T1: letter task, T2: color task) and participants only need to respond to the second task if the first task is a no-go trial and requires no response. Consequently, any trial that requires a T1 response ends after that response is executed. T2 only requires a response if T1 is a no-go stimulus. Thus, T2 is more important in the PRP paradigm, where T2 always requires a response compared to the PP paradigm. Due to paradigm-specific task requirements, participants also are required to coordinate two overt motor responses in the PRP paradigm, but not in the PP paradigm.

Interestingly, even though the PRP and the PP paradigm share many observable commonalities (Miller & Durst, 2015), baseline differences in first task performance can be observed between the two paradigms, as participants are required to respond to T2 more often in the PRP paradigm (i.e., task frequency). Accordingly, Miller and Durst (2015) found shorter RT1 s in the PP paradigm than in the PRP paradigm. Similarly, Mittelstädt and Miller (2017) also found better T1 performance in the PP compared to PRP paradigm. Critically, they observed this performance difference also without presenting a second task stimulus and this was interpreted for differences in task preparation in advance of a trial (or stimulus onset) due to the task requirements.

The present study further examines why RT1 is slower in the PRP compared to the PP paradigm. As elaborated above, the two paradigms differ in their relative importance of the two tasks. It seems reasonable to attribute the differences between the PP and the PRP paradigm to a limited capacity of task preparation because of the requirement to keep the two task sets active in working memory (Miller & Durst, 2015; Mittelstädt & Miller, 2017).

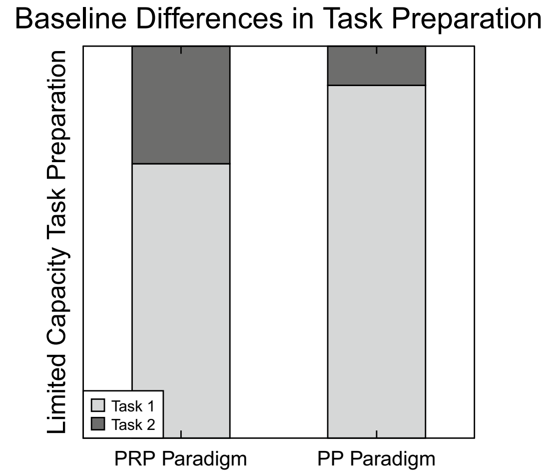

Fig. 1 Assumed baseline differences in task preparation that is assumed to be a limited capacity between the psychological refractory period (PRP) paradigm and the prioritized processing (PP) paradigm. As is illustrated, in the PP paradigm task preparation for the first task is higher than in the PRP paradigm

However, in the previous studies, task preparation was not directly manipulated. Thus, it is not clear whether the baseline differences actually result from specific differences in preparation (i.e., higher preparation for T1 in the PP compared to the PRP paradigm, Fig. 1) or whether the differences also result from another source which is only present in one paradigm. As mentioned above, for example, only in the PRP but not in the PP paradigm, participants are required to coordinate to overt motor responses.

Generally, it seems clear that due to the task requirements of the two paradigms, T1 has a higher priority in the PP than in the PRP paradigm. In the present setting, we consider task prioritization as the general, long-term, objective difference in task requirements between the two paradigms, whereas task preparation is a theoretical account for the performance differences. Thus, in the present study, we investigate whether task preparation can be adapted flexibly. Using reward is one way to manipulate task preparation (e.g., Capa, Bouquet, Dreher, & Dufour, 2013; Kleinsorge & Rinkenauer, 2012; Schevernels, Krebs, Santens, Woldorff, & Boehler, 2014; Zedelius, Veling, Bijleveld, & Aarts, 2012, also see Greenhouse & Wessel, 2013, for a direct physiological link between reward and task preparation).

Here, we aimed to manipulate task preparation by differentially rewarding the two tasks in these two dual-task settings. In both experiments, one of the two tasks yielded a high reward and the other task a low reward. Furthermore, to compare the influence of reward on task preparation between paradigms, participants performed either the PRP or the PP paradigm. The major goal of the present

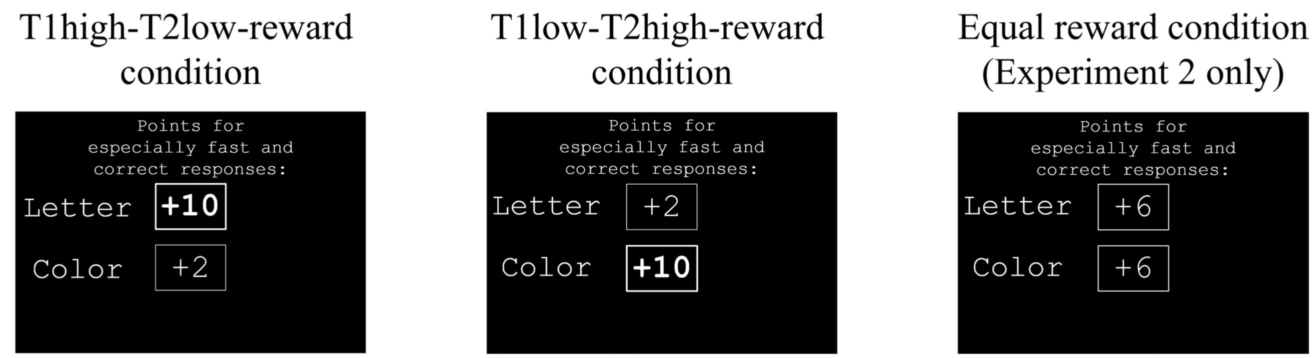

Fig. 2 Three reward conditions that were used in Experiment 2. These payoff matrices were shown in advance of every block to indicate which was the highly rewarded task, indicated by the number of points and the thickness of the rectangles. In Experiment 1, there was no equal reward condition. T1: task 1, T2: task 2

experiments was to investigate the empirical differences of T1 performance between the two paradigms (Miller & Durst, 2015, Mittelstädt & Miller, 2017) by means of a reward manipulation.

As the baseline differences are illustrated in Fig. 1, participants in the PRP paradigm have more preparatory capacity remaining that can be allocated to T1 than participants in the PP paradigm. Thus, one would expect to find a larger reward effect for T1 in the PRP paradigm than in the PP paradigm for when T1 is highly rewarded.

As a full understanding of the processes involved in dual-task performance requires to consider both T1 and T2 performance, the present experiments also allowed us to investigate whether and how the reward manipulation influences T2 performance in the two paradigms. Although the predictions for T2 are less clear, adopting a preparation-based account in similar manner for T2 as for T1, one would expect to find a smaller reward effect in the PRP than in the PP paradigm when T2 is highly rewarded. Alternative reward-dependent performance changes are also possible, as the two paradigms also presumably differ in the amount of coordination of the two tasks that is necessary (i.e., more coordination in the PRP paradigm, since most trials require two motor responses), there might also be more flexibility regarding T2 preparation in the PP paradigm than in the PRP paradigm.

Summarizing, if only less preparatory capacity remaining in the PRP paradigm contributes to the paradigm differences, then we should find a stronger reward effect in the PRP than in the PP paradigm for T1 compared to a baseline (Experiment 2). If this is not the case, it would indicate that other processes additionally modulate the impact of reward in the two paradigms. Although the predictions for RT2 are less clear, investigating whether and how reward influences T2 performance in the two paradigms might also shed further light on the between-paradigm differences.

Experiment 1

We compared performance in the PRP and the PP paradigm in two reward conditions. Specifically, in one condition, participants were able to gain high reward for the first task and at the same time low reward for the second task (i.e., T1high–T2low). In the other condition, participants were able to gain low reward for the first task and high reward for the second task (i.e., T1low–T2high). Reward was manipulated across blocks, but alternated blockwise—that is, participants were informed about the payoff matrix (see Fig. 2) prior to any block. Thus, reward conditions were constant within a block and we used short blocks, so that participants were forced to adapt to a new reward condition after every 45 trials. To avoid any influence by prior experience with the other paradigm, we varied paradigm between participants. We used the tasks used by Miller and Durst (2015)—a letter task for T1 and a color task for T2. Both tasks featured two go stimuli and one no-go stimulus to ensure better comparability between the PRP paradigm and the PP paradigm.

Method

Participants

40 students (28 female) from the University of Freiburg participated in the experiment for either course credits or monetary compensation (7 Euro). All participants were able to earn bonus money of up to 5 Euro, depending on their performance. On average, the bonus money the participants earned was 3.45 Euro ($SD = 0.28$) in the PP paradigm and 4.03 Euro ($SD = 0.20$) in the PRP paradigm. Participants ranged in age from 20 to 29 ($M = 23.16$) and 36 were right-handed. One participant in the PP paradigm was not included in any further analyses due to accuracy below 80%.

Apparatus and Stimuli

The experiment took place in individual test rooms. Stimulus presentation and data collection were controlled by E-Prime 2.0 software (Schneider, Eschman, & Zuccolotto, 2012) running on Fujitso Esprimo P920-0 computers with a 24 inch monitor. Viewing distance was approximately 60 cm, but not restrained.

A centered plus sign served as a fixation cross. Letter stimuli (H, K, and S) were presented at the position of the fixation cross. A colored square around the letter stimulus served as the color stimulus and was 1.48° in length and 0.10° in thickness. The three different color stimuli were blue, green, and red. Thus, there were nine possible stimulus combinations.

Participants responded to the letter task (i.e., T1) with their left and right index fingers (or a no-go response), pressing the "w" and "o" keys, respectively. The responses for the color tasks (i.e., T2) were given with the left and right middle fingers (or a no-go response), pressing the "q" and "p" keys, respectively.

Payoff matrix

Prior to every experimental block, a payoff matrix was presented to the participants to indicate the possible reward earning for each task in the upcoming block. The different payoff matrices are visualized in Fig. 2. In Experiment 1, there were two different payoff schemes and participants could always earn ten bonus points in the high reward task and two bonus points in the low reward task. Depending on reward condition, participants were thus shown either a "+10" or a "+2" for the two tasks with a white rectangle surrounding the numbers (sized 2.10° horizontally and 0.86° vertically). The rectangles appeared vertically centered on the screen, and 0.17° above and below screen center, respectively. Left to the rectangles, the German words for letter (*Buchstabe*) and color (*Farbe*) were used to indicate which task yields how many points. When either the letter task or the color task was going to be rewarded with ten points, the rectangle's thickness varied depending on reward condition: thickness was 1 mm for the task that scored ten points and 0.5 mm for the task that scored two points. Above the payoff matrix, participants read the instruction which informed them they will receive points for, especially fast and correct responses.

Participants received points after successful trial completion, but only if the response to any given task was faster than the respective mean RT. Trials with a correct no-go response yielded points for that no-go task, since a no-go response could not result in an RT for that trial. Moreover, participants only received points when they de facto worked on the task. That is, since in the PRP paradigm, trials with a go-T1 and a no-go T2 were terminated after the response to T1 (and participants had no opportunity to correctly not respond to T2), participants could only receive rewards for T1. In the PP paradigm, participants could only receive rewards for T2 if T1 was the no-go stimulus.

The feedback screen looked fairly similar to the payoff matrix screen, with essential differences to indicate points scored. If points were scored in the previous trial, the rectangle showed three black Euro symbols (€) and was filled in white for the tasks that yielded points in the preceding trial. Moreover, a white plus-sign (+) appeared between task label and rectangle. If no points were scored, but the answer was correct, the rectangles remained filled in black with neither Euro symbols nor a plus sign appearing. If any response was either erroneous or the response window was incorrectly exceeded, the German word for wrong (*falsch*) appeared centered on screen. Moreover, the total amount of points scored in the experiment was permanently displayed, horizontally centered on top of the screen.

Procedure

Half of the participants were tested in the PRP paradigm, whereas the other half was tested in the PP paradigm.

The experiment consisted of three training blocks and 16 experimental blocks. Every block had 45 trials, resulting in 720 trials in the experimental blocks (i.e., 40 trials for every stimulus combination in every reward condition). For each participant, the letter and color stimuli were randomly assigned to one of the three possible responses (i.e., left, right, no-go, for index/middle finger, respectively). The first block served as training for the tasks, with no reward manipulation. The second and third blocks were used as training blocks for the reward manipulation. After every block with reward manipulation, new mean RTs were calculated for both tasks from the previous two blocks. Note that mean RT2 was calculated from correct T1-no-go T2-go trials only, whereas mean RT1 was calculated from all correct trials that required a response to T1.

In the blocks with reward manipulation, the payoff matrix was shown for 10 s at the beginning of every block. Reward condition (i.e., T1high–T2low vs. T1low–T2high) alternated blockwise. It was counterbalanced across participants which of the reward conditions was apparent during odd or even blocks. After the payoff matrix was shown, participants were asked which of the two tasks was going to yield 10 points in the upcoming block and were asked to respond using the "B" key for the letter task and the "F" key for the color task. This was implemented to ensure that they had understood the instructions.

Typical trial sequences along with differences in feedback screens are visualized in Fig. 3. Trials started with a fixation cross for 500 ms. Subsequently, the stimuli appeared on

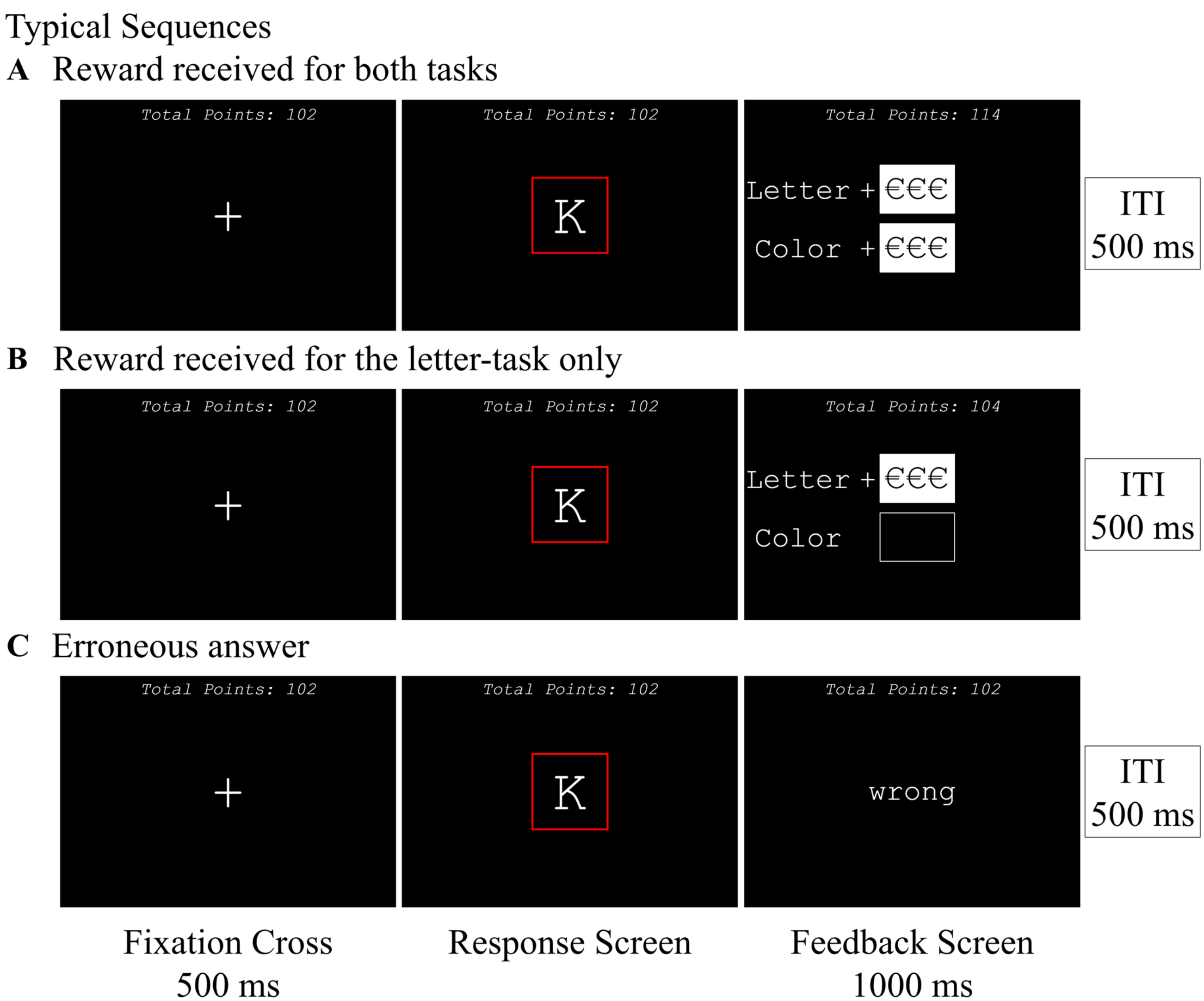

Fig. 3 Typical trial sequences. **a** Illustrates the feedback screen when participants reward for both tasks, **b** illustrates the feedback screen with reward for the first task only, and **c** illustrates the feedback for erroneous trials. The overall points were permanently displayed at the upper edge of the screen. Trials were always followed by an inter-trial interval (ITI) of 500 ms, where a black screen was shown

screen simultaneously. Every trial, one of the nine possible stimulus combinations (i.e., one of the three letter stimuli and one of the three color stimuli) was randomly selected so that every combination occurred five times per block.[1] Stimuli remained on screen for a maximum of 2000 ms or until a response was given. For trials that required two responses (which were only possible in the PRP paradigm), stimuli remained on screen for another 2000 ms or until a second response was made. Task-order reversals were coded as erroneous and entailed according feedback. Feedback was displayed for 1000 ms in the above-described way, followed by an inter-trial interval of 500 ms.

The trial procedure was largely the same in the task-training block except for the following differences. If participants answered correctly, the German word for correct (*Richtig*) appeared on screen for 500 ms. If participants made an error or incorrectly exceeded the response window, a feedback screen with the task instructions appeared, and participants were able to proceed to the next trial by pressing the space bar.

At the beginning of the experiment, participants were instructed how to categorize the letter stimuli with their index fingers (and which letter required no response, i.e., no-go) and the color stimuli with their middle fingers (and which color required no response, i.e., no-go). That is, one

[1] Note however, that due to programming errors in the PRP paradigm in Experiment 1 it was theoretically possible that one stimulus combination was selected up to a maximum of eight times.

of the letter/color stimuli was associated with a right-hand press, a left-hand press, or a no-go response, resulting in a total of nine stimulus combinations (i.e., four T1-go T2-go combinations, two T1-go T2-no-go combinations, two T1-no-go T2-go combinations, and one T1-no-go T2-no-go combination). Moreover, participants were instructed to respond as quickly and accurately as possible. The remainder of the instructions differed between the two paradigms.

In the PRP paradigm, participants were instructed to first respond to the letter task with the corresponding index fingers if one of the go-letters was shown and to withhold any response if the no-go letter was shown. Participants were asked to subsequently respond to the color stimulus with the corresponding middle fingers if one of the go color stimuli was shown and to withhold any response if the no-go color stimulus was shown.

In the PP paradigm, participants were instructed to first respond to the letter in the same way as in the PRP paradigm. The instruction for T2 differed, however. Participants were instructed to respond to the color stimuli only when the letter stimulus was the no-go stimulus. As in the PRP paradigm, participants had to respond with one of their middle fingers to the go stimuli of the color task and withhold any response if the no-go color was presented.

Prior to the first block with reward, the payoff matrix was explained. Participants received information on the two possible payoff schemes and how these schemes were visualized in the experiment. Moreover, participants were informed about the design of the feedback screen. The first two blocks with reward served as training blocks for the reward manipulation. Thus, after the first two blocks with reward, the overall score was set back to zero and participants were instructed to score as many points as possible thereafter to maximize the monetary reward.

Design

The two reward conditions alternated blockwise, serving as a within-subject factor, and paradigm was varied as a between-subject factor. Consequently, a 2 (reward: T1high–T2low vs. T1low–T2high) × 2 (paradigm: PRP vs. PP) repeated-measures mixed-design was applied.

Results

Only the experimental blocks were used for data analysis. All catch trials (i.e., no-go no-go trials) were also excluded from any further analyses (1/9 of all trials). For RT analyses in the remaining trials, we excluded all trials in which any error was made (9.09%).

To compare the two paradigms as fairly as possible, we restricted the T1 analyses to trials that required a go response for T1 and a no-go response for T2 (2/9 of all trials). Thus, only a response to T1 was required in both paradigms.[2] Conversely, T2 analyses were also restricted to trials with the same trial category to ensure a fair between-paradigm analysis. Thus, only trials that required a no-go T1 and a go T2 response were used (2/9 of all trials).

For the percentage of errors (PE) analyses, we classified trials as erroneous if participants a) pressed an incorrect response key for the go task, b) did not respond within the response window for the go task or c) responded to the no-go task instead of the go-task. The PE committed in the trial category for the T1 and T2 analyses are denoted by PE1 and PE2, respectively.

Letter task analyses: RT1 and PE1

Figure 4a shows the means of RT1 for the two reward conditions as a function of paradigm. An ANOVA with the within-subject factor reward condition and the between-subject factor paradigm was conducted on RT1. This ANOVA revealed a main effect of reward, $F(1, 37) = 20.68$, $p < .001$, $\eta_p^2 = .359$, with responses being faster in the T1high–T2low condition (537 ms) than in the T1low–T2high condition (572 ms), resulting in a 35 ms reward effect. Moreover, the main effect of paradigm was significant, $F(1, 37) = 9.42$, $p = .004$, $\eta_p^2 = .203$, indicating that T1 responses were faster in the PP paradigm (512 ms) than in the PRP paradigm (597 ms), resulting in an 85 ms effect of paradigm. The task reward × paradigm interaction was not significant ($p = .555$).

A parallel analysis was run for PE1 and the corresponding means are displayed in Fig. 4b. The ANOVA revealed no significant effects (all ps > .319).

Color task analyses: RT2 and PE2

Figure 4c shows the means for RT2 for the two reward conditions as a function of paradigm. An ANOVA parallel to the RT1 analysis was run for RT2. The main effect of reward was significant, $F(1, 37) = 16.55$, $p < .001$, $\eta_p^2 = .309$, with responses to T2 being faster in the T1low–T2high condition (755 ms) than in the T1highT-2low condition (800 ms). The main effect of paradigm was not significant ($p = .518$), indicating no differences between the PRP (790 ms) and the PP (765 ms) paradigm. Interestingly, the interaction of task reward × paradigm was significant, $F(1, 37) = 7.68$, $p = .009$, $\eta_p^2 = .172$, indicating a significantly stronger benefit from the T1low–T2high condition in the PP (75 ms) than in

[2] In both experiments, the results were quite similar for RT1 and RT2 when running the analyses for all trials instead of restricting analyses to the same trial categories.

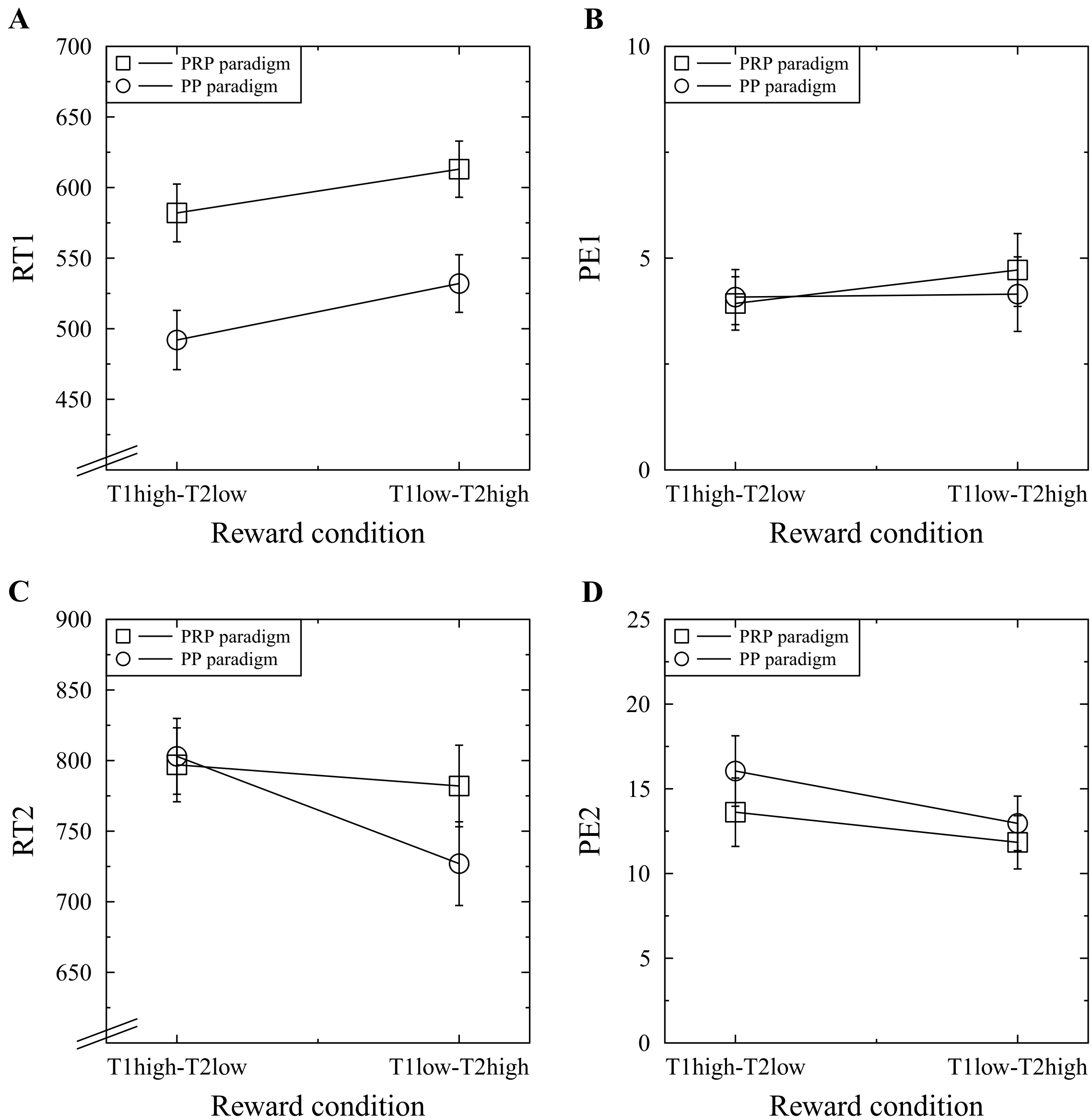

Fig. 4 Results on letter task RT (**a**), letter task PE (**b**), color task RT (**c**), and color task PE (**d**) for the two reward conditions (T1high–T2low vs. T1low–T2high) separately for both paradigms (PRP vs. PP). Error bars depict mean standard errors. *RT* reaction time, *PE* percent errors, *PRP* psychological refractory period, *PP* prioritized processing

the PRP (14 ms) paradigm. Separate *t* tests for each paradigm showed that only the difference between the two reward conditions in the PP paradigm was significant, $t(18) = 3.97$, $p = .001$, $d = 0.514$, but not in the PRP paradigm, $t(19) = 1.22$, $p = .236$, $d = 0.148$.

Again, we ran a parallel analysis for PE2 with the same trial restrictions as mentioned above. The PE2 results are depicted in Fig. 4d. The ANOVA revealed a significant main effect of reward, $F(1, 37) = 4.41$, $p = .043$, $\eta_p^2 = .107$, indicating fewer errors in the T1low–T2high condition (12.73%) than in the T1highT2low condition (14.51%). No other effects were significant, $ps > .449$.

Discussion

Experiment 1 demonstrated that only T1 (but not T2) performance improves in both the PP and the PRP paradigm when T1 reward was high (and T2 reward low) compared to when T1 reward was low (and T2 reward high). This selective performance increase suggests that participants were able to differentially prepare the two task sets in both multitasking paradigms. We also replicated the typical between-paradigm differences in RT1 and these between-paradigm differences have previously been attributed to differences in both task preparation (i.e., more preparation for T1 in the PP paradigm) as well as online-processing (i.e., more parallel processing in the PRP paradigm), based on a higher prioritization of T1 in the PP than in the PRP paradigm (Miller & Durst, 2015; Mittelstädt & Miller, 2017).

The reward condition results showed the reversed pattern for RT2, reflected in faster T2 responses in the T1low–T2high condition than in the T1high–T2low condition. Interestingly, the influence of reward was modulated by paradigm, with a selective RT2 difference between the conditions being significant only in the PP paradigm, as indicated by separate post hoc tests. Before discussing this finding in more detail, we will see whether the differential influences of reward on T2 performance will replicate in a setting which also includes an equal reward condition as a baseline.

In the error data, there was also a reward effect for T2 with fewer errors in the T1low–T2high condition than in the T1high–T2low condition. Other than this finding, no other effect was significant in the error data and the numerical differences were rather small.

To summarize the findings of Experiment 1, it is fair to say that the implementation of the reward manipulation worked in both paradigms, especially for T1. Moreover, the between-paradigm differences in RT1 remained. Our goal for Experiment 2 was, therefore, to further investigate possible differential reward effects between the two paradigms. Specifically, reward-manipulating within the two paradigms might be more conclusive when including an equal reward condition as a baseline—especially when considering the baseline differences T1 performance between the two paradigms.

Experiment 2

Including a baseline condition with equal reward for both tasks could reveal differential effects for RT1. Again, consider the baseline differences in task preparation between the PP paradigm and the PRP paradigm (Fig. 1), as indicated by RT1 differences (Miller & Durst, 2015; Mittelstädt & Miller, 2017). Here, without any reward manipulation, participants are more strongly prepared for T1 in the PP paradigm than in the PRP paradigm. Assumed that task preparation is a limited capacity, one could thus argue that in the PRP paradigm, participants should have more preparation "left" for T1 than in the PP paradigm—possibly allowing for a stronger reward effect between an equal reward condition and the T1high–T2low condition in the PRP paradigm than in the PP paradigm.

Experiment 2 had two major goals. First, we wanted to examine whether there are differential effects for RT1 when considering a baseline (i.e., equal reward) condition. This interaction (or lack thereof) could help locate the source of the baseline between-paradigm differences. Specifically, if this interaction is present, this could hint at task preparation as the source of baseline differences between the paradigms. If this interaction is not present, however, this could hint at an additional source of interference that differs between the paradigms. Second, we wanted to see whether the interaction in RT2 replicates when including a baseline condition.

Method

Participants

A fresh sample of 40 students (26 female) from the University of Freiburg participated for either course credits or monetary compensation. As in the first experiment, participants could earn bonus money up to five Euro depending on performance. On average, participants earned bonus money of 2.82 Euro ($SD = 0.32$) in the PP paradigm and 2.94 Euro ($SD = 0.26$) in the PRP paradigm. Participants ranged in age from 18 to 30 ($M = 23.45$) and 39 were right-handed. One additional subject was also tested, but excluded because of major difficulties with the tasks, which was also reflected in low bonus points total. Moreover, two participants in the PP paradigm were excluded from any further analyses due to accuracy below 80%.

Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and instructions were the same as in Experiment 1 except for the following changes. As mentioned above, a third reward condition was used (i.e., equal reward condition). The payoff matrix presented prior to every block was similar to the other two reward conditions (see Fig. 2). That is, to indicate reward in the upcoming block, a "+ 6" was shown next to both task labels surrounded by a white rectangle. Moreover, the rectangles' thickness was 0.75 mm for both tasks. Additionally, on the screen which asked participants which task was rewarded how much, an equal reward option was added ("G" key). A third reward training block was added for the equal reward condition. The overall number of blocks remained the same. Consequently, the number of experimental trials was reduced to 675 trials (i.e., 25

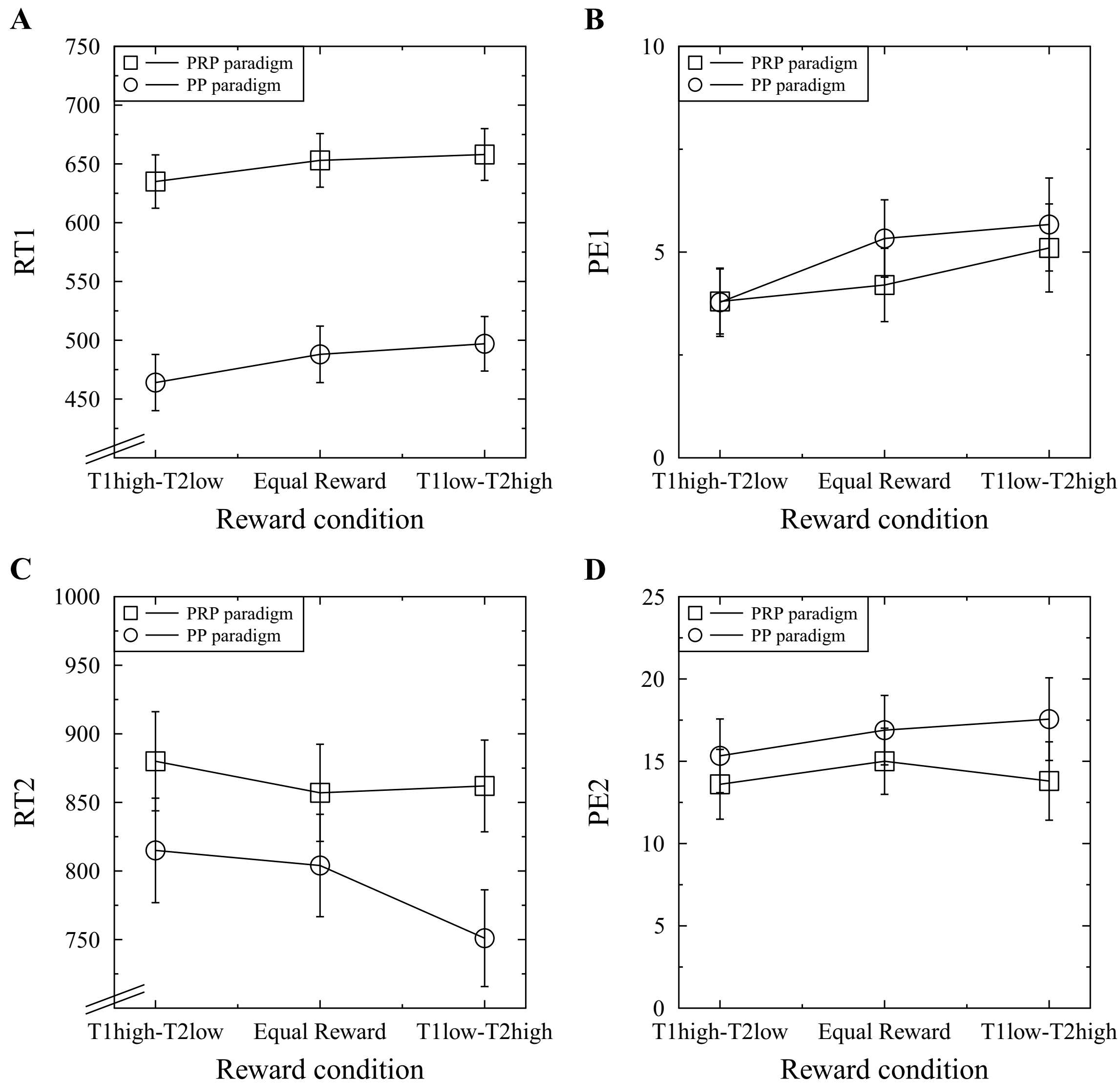

Fig. 5 Results on letter task RT (**a**), letter task PE (**b**), color task RT (**c**), and color task PE (**d**) for the three reward conditions (T1high–T2low vs. equal reward vs. T1low–T2high) separately for both paradigms (PRP vs. PP). Error bars depict mean standard errors. *RT* reaction time, *PE* percent errors, *PRP* psychological refractory period, *PP* prioritized processing

trials for every stimulus combination in every reward condition) and every reward condition was used in six blocks throughout the experiment. Reward conditions were varied randomly within a triplet of blocks. After every three blocks, new mean RTs from the correct responses in these blocks were calculated as the time to beat for participants to get the bonus points.[3] A 3 (reward: T1high–T2low vs. equal reward vs. T1low–T2high) × 2 (paradigm: PRP vs. PP) repeated-measures mixed-design was applied.

Results

Only trials from the experimental blocks were used for the data analysis. Again, we excluded all catch trials (1/9 of all trials). For the RT analyses, trials in which any error was made (10.22%) were excluded. PEs were classified as in Experiment 1.

Whenever the assumption of sphericity is violated, Greenhouse–Geisser corrected results are reported. The *p* values of all pairwise comparisons for the reward conditions are Bonferroni corrected.

[3] In Experiment 2, mean RTs were calculated from all correct responses for the respective task.

Letter task analyses: RT1 and PE1

We again restricted T1 analyses to trials with a go no-go sequence to ensure better comparability between the paradigms. Figure 5a shows the means of RT1 for the three reward conditions as a function of paradigm. An ANOVA with the within-subject factor reward condition and the between-subject factor paradigm was conducted on RT1. This ANOVA revealed a main effect of reward, $F(2, 35) = 6.98$, $p = .002$, $\eta_p^2 = .162$. Pairwise comparisons revealed significant differences between the T1highT2low condition (549 ms) and the equal reward condition (570 ms), $p = .023$, as well as between the T1high–T2low condition and the T1low–T2high condition (578 ms), $p = .004$. The difference between the equal reward condition and the T1low–T2high condition was not significant ($p > .999$). Moreover, the main effect of paradigm was significant, $F(1, 36) = 27.99$, $p < .001$, $\eta_p^2 = .437$, indicating that T1 responses were faster in the PP paradigm (483 ms) than in the PRP paradigm (649 ms). The reward condition × paradigm interaction was not significant, however ($p = .812$).

A parallel analysis was run for PE1. The corresponding means are visualized in Fig. 5b. In the ANOVA, the main effect of reward just failed to reach significance, $F(2, 35) = 3.10$, $p = .051$, $\eta_p^2 = .079$. Descriptively more errors were committed the less reward T1 yielded (T1high–T2low: 3.79%, equal reward: 4.77%, T1low–T2high: 5.38%). No other effect approached significance, $ps > .618$.

Color task analyses: RT2 and PE2

As in Experiment 1, we again restricted color task analyses to T1-no-go T2-go trials to ensure a fair comparison. Figure 5c shows the corresponding means for RT2 for the three reward conditions as a function of paradigm.

An ANOVA parallel to the RT1 analysis was run. We found a significant main effect of reward condition, $F(2, 35) = 6.97$, $p = .002$, $\eta_p^2 = .162$. Pairwise comparisons showed a significant difference between the T1high–T2low (848 ms) and the T1low–T2high conditions (807 ms), $p = .008$. None of the comparisons including the equal reward condition (830 ms) were significant, $ps > .999$. The main effect of paradigm was not significant, $F(1, 36) = 2.41$, $p = .130$, $\eta_p^2 = .063$, indicating no between-paradigm differences (PRP: 866 ms, PP 790 ms). As in Experiment 1, we found a reward × paradigm interaction, $F(2, 35) = 3.88$, $p = .025$, $\eta_p^2 = .097$, again indicating a stronger reward effect between the T1high–T2low and the T1low–T2high conditions in the PP paradigm (64 ms) than in the PRP paradigm (18 ms).

Separate post hoc ANOVAs were conducted for each paradigm with reward condition as the within-subject factor. The results showed that there was only a significant main effect of reward in the PP paradigm, $F(2, 16) = 7.06$, $p = .003$, $\eta_p^2 = .293$, with significant differences between the T1highT2low condition (815 ms) and the T1low–T2high condition (751 ms), $p = .028$, revealed by pairwise comparisons. The difference between the equal reward condition (804 ms) and the T1low–T2high condition was also significant, $p = .019$. The difference between the T1high–T2low and the equal reward condition was not significant, $p > .999$. The main effect of reward was not significant in the PRP paradigm, $F(2, 18) = 1.75$, $p = .188$, $\eta_p^2 = .084$.

A parallel analysis was run for PE2. The corresponding means can be found in Fig. 5d. This ANOVA did not reveal any significant effects, $ps > .374$.

Discussion

In Experiment 2, we added a baseline condition with equal reward for both tasks. We again found a significant reward effect on T1 performance, with selectively faster responses in the T1high–T2low condition than in the baseline or T1low–T2high conditions. Moreover, the between-paradigm effect with slower responses in the PRP than in the PP paradigm was also replicated. Most interestingly, we did not find an interaction of reward condition and paradigm, indicating no differences in the reward effects between the PRP paradigm and the PP paradigm for T1. Instead, the results of Experiment 2 were very consistent with the findings of Experiment 1 which did not include a baseline condition. Importantly, the results were also consistent regarding the observed interaction for RT2, in that again only in the PP paradigm, there was a significant reward effect.

In the analyses of the error data, a descriptively similar result pattern emerged for PE1 as for RT1. For PE2, no straightforward result pattern was found, with only very small numerical differences between the reward conditions.

General discussion

The purpose of the present study was to investigate whether differences in RT1 between dual-task paradigms (i.e., the PRP paradigm and the PP paradigm) are due to differences in task preparation which we intended to manipulate by means of a reward manipulation. Moreover, we investigated the flexibility of T2 performance in the two paradigms.

The main findings can be summarized as follows: (a) we observed no interaction between paradigm and reward condition for RT1 when including a baseline condition. This shows that in both paradigms, participants adapted similarly to the reward manipulation, indicating a certain flexibility. Note that in both the PRP and PP paradigm, participants were able to adapt their RT1 performance to the reward manipulation. Moreover, there was (b) an interaction between paradigm and reward condition for RT2 with reward effects on RT2 only in the PP paradigm.

The results suggest that task preparation for the individual task in a dual-task setting contributes to dual-task performance. Yet, it should be noted that one needs to consider the possibility that reward may potentially not be directly linked to preparatory processing—however, based on previous findings (Capa et al., 2013; Greenhouse & Wessel, 2013; Kleinsorge & Rinkenauer, 2012; Schevernels et al., 2014; Zedelius et al., 2012), it seems like the most likely theoretical account. More specifically, the faster first task RTs in the T1high–T2low condition implicate that even though the overall task instruction remained the same, participants were still flexible enough to adjust their task preparation to the reward condition. The allocation of preparatory capacity occurred rather flexible. Since short blocks of 45 trials per block were used, participants were forced to adapt fairly quickly to new reward conditions and thus flexibly adjust their task preparation.

Taken together, the present results (i.e., the T1 performance improvements when this task was highly rewarded) suggest that individuals are capable of adapting to different task requirements. However, although our findings suggest a certain flexibility, the results also hint at limits in the allocation of preparatory capacity, as indicated by (a) the lack of interaction effects between paradigm and reward condition in Experiment 2 and (b) the lack of reward effects on T2 in the PRP paradigm.

When revisiting the assumed baseline differences in task preparation in Fig. 1, one could assume that in both paradigms, preparatory capacity was shifted towards T1 in the T1high–T2low condition. However, since the between-paradigm differences remained and there was no interaction, it seems likely that the amount of preparatory resources shifted did not differ between both paradigms (also indicated by the lack of an interaction effect in Experiment 2, contrary to our expectations). Thus, the results suggest that the baseline difference between the two paradigms in RT1 is presumably not just due to differences in task preparation. Assuming that task preparation was the single process underlying the baseline differences, there should have been an interaction between reward condition and paradigm in Experiment 2. Given this finding, it seems reasonable to assume that the baseline differences result from a source which is only present in one paradigm. Specifically, besides the differences in online processing (Mittelstädt & Miller, 2017) and task preparation (Miller & Durst, 2015; Mittelstädt & Miller, 2017), another major difference between the two paradigms is that the PRP paradigm mostly requires subjects to coordinate two motor responses in one trial, possibly restricting the flexibility of allocating preparatory capacity to T1 in the PRP paradigm.

This latter account seems especially captivating given the lack of reward effects on T2 in the PRP paradigm. That is, in both experiments, there was only a small numerical trend towards faster RT2 s, and only in Experiment 1, we found a significant reward effect on PE2 in the PRP paradigm. This finding converges well with the findings of van Selst and Jolicoeur (1997) who also did not find any reward effects in RT2. Since the same manipulation had an effect in the PP paradigm, it is fair to say that the lack of reward effects in T2 in the PRP paradigm is not due to an ineffective manipulation. Rather, it seems likely that the coordination of two overt responses in the PRP paradigm contributes to the performance differences between the paradigms—and a decreased adaptability for T2 in the PRP paradigm.

This point of view is strengthened by reward effects on the inter-response interval (IRI) in the PRP paradigms T1-go T2-go trials. IRI analyses can help subtract out T1 dependencies on RT2 (e.g., De Jong, 1993; Keele, 1973) and could, therefore, possibly allow disentangling RT2 effects from the motor coordination that was necessary. In both experiments, we find that the IRI was significantly smaller, the more reward T2 yielded[4] [Experiment 1: $t(19) = 2.11$, $p = .048$, $d = 0.215$, Experiment 2: $F(2, 18) = 14.29$, $p < .001$, $\eta_p^2 = .429$]. In the PRP paradigm, the coordination of the two motor responses is indeed influenced by the reward manipulation. Thus, the allocation of preparatory capacity for T2 could have been less flexible due to the coordination of two motor responses in the PRP paradigm.

Thus, to reconcile the findings of both T1 and T2, it seems necessary to postulate a source of interference that differs between paradigms in addition to differences in task preparation. Since the number of potential responses is another fundamental between-paradigm difference, these findings could indicate that the coordination of two responses plays a crucial role in the baseline between-paradigm differences. More specifically, since four-ninths of all trials were T1-go T2-go trials, participants in the PRP paradigm often had to coordinate two overt responses in a trial. On the contrary, in the PP paradigm, T1-go T2-go trials were terminated after R1. Consequently, no coordination of two responses was ever necessary for participants in the PP paradigm leading to higher flexibility of T2-preparation. One possibility to further investigate this post hoc interpretation could be the use

[4] In Experiment 1, the IRI in the T1highT2low condition (235 ms) was bigger than in the IRI T1lowT2high condition (221 ms). In Experiment 2, pairwise comparisons revealed significant differences in the IRI in the T1high-T2low-condition (189 ms) and the equal reward condition (176 ms), $p < .001$, as well as the T1low-T2high-condition (161 ms), $p = .023$. The difference between the equal reward condition and the T1low-T2high-condition was not significant, $p = .127$.

of different modalities—that is, motor coordination costs might decrease using different modalities for the responses of the two tasks (e.g., Hazeltine & Ruthruff, 2006; Wickens, 2002), for example, using a motor response for T1 and a vocal response for T2.

Future research will be needed to examine the limits of task prioritization—that is, when increasing the frequency of T1-no-go T2-go trials in the PRP paradigm in the present experimental setup, one should expect to find a reward effect if the lack of effects in the present study were due to task coordination costs. On the contrary, if there is a limit for task prioritization of T2, no reward effect on T2 should occur even when increasing the frequency of T1-no-go T2-go trials.

Summarizing, the present results show additive effects of reward on T1 performance in the PP and PRP paradigms and interactive effects on T2 performance (with a lack of reward effects in the PRP paradigm). These findings hint at a limit in the allocation of preparatory capacity to a second task if the first task always needs to be executed first. That is, the coordination of two motor responses (only required in the PRP but not in the PP paradigm) seems likely to play a role in (a) the baseline differences in RT1 between the PRP and PP paradigm and (b) in the lack of reward effects on T2 in the PRP paradigm.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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

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