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ORIGINAL ARTICLE

The role of feedback delay in dual-task performance

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Abstract Doing two things at once is hard, and it is probably hard for various reasons. Here we aim to demonstrate that one so far barely considered reason is the monitoring of sensory action feedback, which detracts from processing of other concurrent tasks. To demonstrate this, we engaged participants in a psychological refractory period paradigm. The responses in the two tasks produced visual action effects. These effects occurred either immediately or they were delayed for the first of the two responses. We assumed that delaying these effects would engage a process of monitoring visual feedback longer, and delay a concurrent task more, as compared to immediate effects. This prediction was confirmed in two experiments. We discuss the reasons for feedback monitoring and its possible contribution to dual tasking.

Introduction

Doing two tasks at once typically delays at least one of the tasks as compared to doing only one task at a time. For example, when humans are to respond as quickly as possible to two stimuli presented in quick succession, responding to the second stimulus usually takes longer as compared to presenting the stimuli with a long delay, and hence less overlap between tasks (Telford, 1931). This observation was coined the psychological refractory period (PRP) effect (Pashler & Johnston, 1989; Welford, 1952). The PRP effect is a stable phenomenon obtained with a variety of stimuli and responses, and only few exceptions were reported to date (see Janczyk, Pfister, Wallmeier, & Kunde, 2014). Common explanations of the PRP effect assume that there is one stage of information processing in between encoding stimuli and executing a motor response that is capacity-limited. Thus, this stage cannot run at all, or not with the same efficiency, in two tasks at the same time (Navon & Miller, 2002; Pashler, 1994; Tombu & Jolicoeur, 2003). Consequently, the concurrent operation of this process is considered either impossible, or at least avoided for strategic reasons (e.g., Meyer & Kieras, 1997; Miller, Ulrich, & Rolke, 2009). Importantly, this process is located before execution of motor responses.

However, it has been suggested at times that also motor activity itself might cause processing limitations for various reasons. For example, Keele (1973) and De Jong (1993) argued that the initiation of a motor response briefly blocks the initiation of other motor responses. Beyond initiation, also the execution of a motor response might interfere with the selection or initiation of other motor responses. The origins of these execution-related decrements are not entirely clear though.

Consider the observation that movements with larger amplitudes delay a secondary task more than movements with shorter amplitudes (Bratzke, Rolke, & Ulrich, 2009; Ulrich et al., 2006). This delay may originate from a genuine motor-related bottleneck, such that the generation of motor output per se blocks the processing of other capacity-limited processes. However, it might equally well originate from a process which Welford (1952) called response monitoring: the processing of sensory feedback from response execution. Conceivably, such monitoring is engaged longer the longer-lasting the feedback from the

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executed motor action is. Therefore, it has turned out notoriously difficult to disentangle processing limitations based on motor execution per se from processing limitations based on processing feedback from this particular motor execution (Bratzke et al., 2008; Pashler & Christian, 1994). When it comes to study the potential impact of feedback monitoring proper on dual tasking, it is thus not ideal to vary the response requirements, because this inevitably varies both, motor output and sensory feedback, at the same time.

In the present paper, we would like to demonstrate more clearly that processing feedback from motor responses can cause interference with concurrent tasks, even when the motor output itself remains the same and only the type of feedback varies. Consequently, we kept the motor output simple and identical (keypresses in either case) but varied the visual feedback from such output. Note, with feedback we denote the sensory effects caused by a motor response, not information regarding the correctness of the response. Such sensory feedback (and its processing) is inevitably involved in every dual-task situation that requires an overt motor response such as a standard PRP task. However, in a typical PRP task feedback is rather proximal to the response such as feeling the own fingers when pressing response keys, or hearing the own voice when making a vocal response. We suggest that Welford’s (1952) original idea of response monitoring, which he seems to limit to the processing of body-related, proximal movement feedback, can be—and should be—extended to processing of more distal sensory effects resulting from motor activities. In other words, we assume a more general process of effect monitoring.

That people in general monitor what they do seems barely disputable. For one, we often intend to achieve specific effects (i.e., goals), and we must ensure whether we ultimately achieved what we intended to achieve (Adams, 1971; Hoffmann et al., 2007). But also when the effects of our actions are not yet predictable, it is essential to keep track of potentially harmful or otherwise relevant events, which are not yet under the actor’s control. Therefore, humans tend to observe the changes they cause (Band et al., 2009). It is less clear though whether such effect monitoring can interfere with processing of other concurrent tasks. In typical button-press experiments, such monitoring costs would not easily become apparent, since the feedback in such experiments is inherent to, and confounded with the efferent activity itself. To disentangle the generation of efferent activity from the monitoring of perceptual effects from that activity, we need situations where motor actions produce effects that go beyond the sensory feedback from the body movement itself.

Consider what might happen when a considerable share of what we caused by our actions occurs somewhat later than the motor activity itself, such as typing at a slow PC which displays the typed letters only after a delay. Assuming that effect monitoring has to proceed until sufficient evidence for the identity of the produced event has accumulated, the duration of this process must be quite extended with delayed action effects. If we also assume that processing other tasks cannot run with the same efficiency in parallel with such monitoring, other tasks could possibly suffer when they are supposed to take place during this extended monitoring interval.

Basically, this is the idea we tested here. We used a standard PRP paradigm, and responses produced visual effects (cf. Fig. 1). These effects occurred either immediately or, crucially, the effect of the first response was delayed, so that monitoring this effect would run into conflict with processes in the second task. The question was whether this temporal overlap between monitoring of effects in Task 1 and processing in Task 2 (such as response selection, see next paragraph) would lead to any decrements in Task 2.

A more formal description of this scenario is shown in Fig. 2. It shows two conditions and the possible processing assumptions for the two experiments we report. The top panel shows the condition without effect delay, meaning that each motor response in a PRP experiment produces immediate sensory feedback (the flashing of one of two “lamps” on a screen, cf. Fig. 1). The assumption is that effect monitoring starts some time prior to the observable response execution, possibly encompassing the tactile feedback from the moving finger prior to hitting the key, and lasts until sufficient evidence for additional feedback, such as visual events, has been gathered. Effect monitoring in Task 1 might interfere with Task 2 processes, such as response selection. Such interference can be modelled differently. Either two capacity-limited processes might operate in a serial fashion (Pashler, 1994), or they might operate in parallel fashion but with varying amounts of capacity shared (Navon & Miller, 2002). Formally, the capacity sharing model is the more general one, with the serial model being a special case in which 100% capacity is first devoted to one task and then to the other (Tombu & Jolicoeur, 2003). As a starting point, we thus considered the more general case, in which effect monitoring might occur simultaneously with other capacity-limited processes, but at the cost of reduced efficiency.

With immediate visual effects (Fig. 2, top panel), there are chances that monitoring of Effect 1 overlaps with response selection in Task 2. However, when the visual effect of the first response is delayed, as shown in the bottom panel, this overlap with response selection in Task 2 is considerably prolonged, thereby increasing RT2. Moreover, the monitoring of the delayed effect might extend up to a point in time when monitoring of the effect

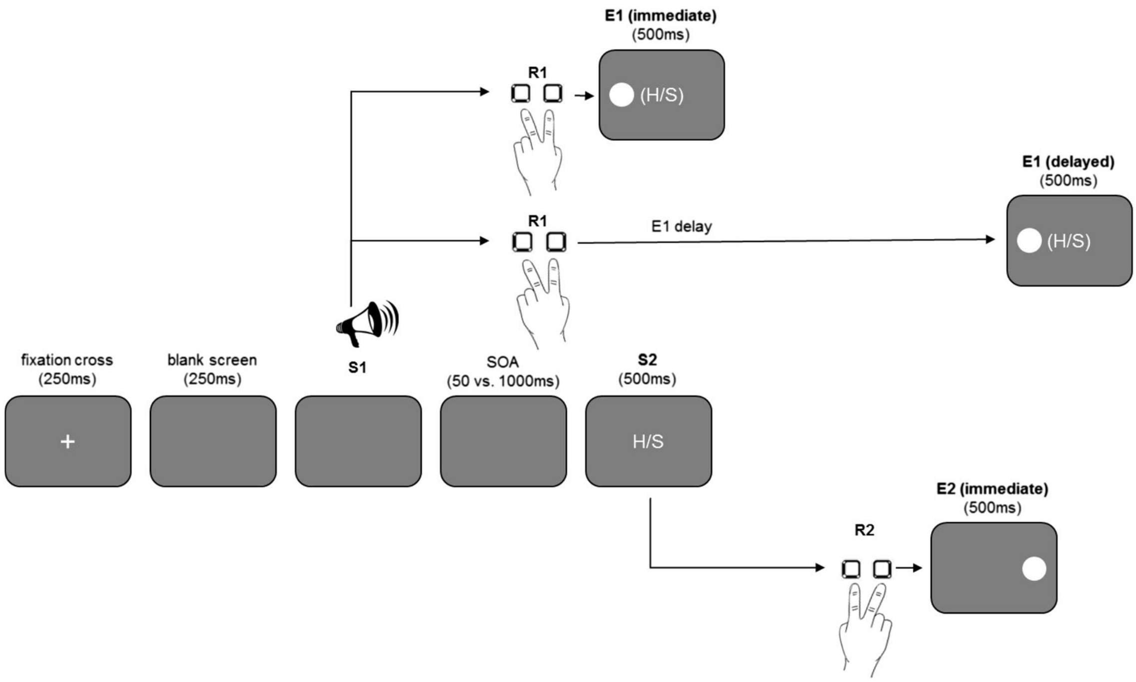

Fig. 1 Procedure used in Experiments 1 and 2. Participants responded to tones of varying pitch in Task 1 and letters of varying identity in Task 2. Each of the responses produced a visual effect, which occurred predictably either with or without a delay in Task 1

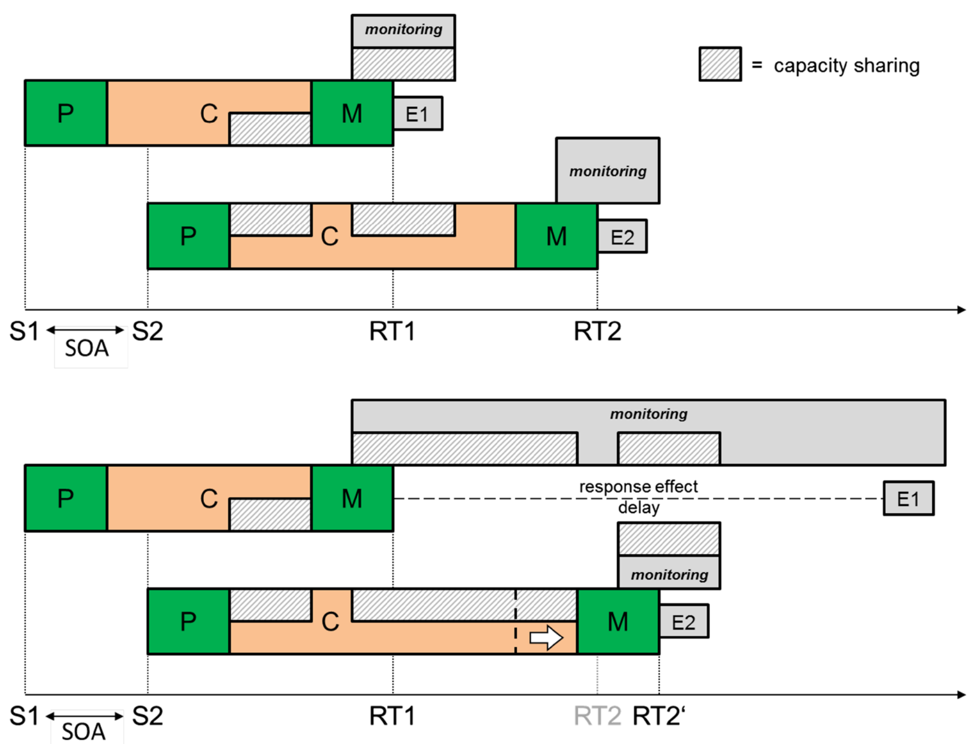

Fig. 2 Illustration of the possible impact of delayed action effects in Task 1 of a Psychological Refractory Period paradigm. The *letters P*, *C*, and *M* denote the perceptual, central, and motor stage of the two tasks. The end of the M stage results in the observable keypress and terminates the RT interval. Effect monitoring starts before the keypress, and lasts until sufficient information on potential response effects has been accumulated. With delayed effects in Task 1 (*bottom panel*), there is longer capacity sharing with response selection in Task 2 and effect monitoring in Task 2. This may increase the response time in the second task with delayed effects (RT2') as compared to immediate effects (RT2). SOA: Stimulus onset asynchrony

of the second task was already required. Such overlap between monitoring processes might perhaps delay the second response as well, if we assume that the initiation of motor output starts only when sufficient capacity for monitoring its sensory feedback is available. This possibility will be discussed in the "General discussion".

The two experiments reported here are very similar. The main difference between them is that participants in

Experiment 1 started with a condition with immediate effects in both tasks first and then encountered a condition with delayed effects in Task 1 in the second half, whereas this order was reversed in Experiment 2 to rule out explanations in terms of fatigue or surprise. Other differences relate to the specific effect delays that were used in the experiments. The main outcome of both experiments is rather consistent, though.

Experiment 1

The idea of Experiment 1 is to delay the sensory effect of a first response in such a way that the still ongoing monitoring of this effect increases the overlap with the required selection of a second response. We used a delay where such overlap would occur with considerable likelihood with both SOAs. At first glance, this might be easily achieved by just having a very long R1-E1-delay. However, participants consider events less likely as effects of their actions the longer the delay between action and effect is (Metcalfe, Eich, & Castel, 2010; Michotte, 1963). Consequently, such a delay should best be a compromise between being long enough to induce overlap with Task 2, and being short enough to be still considered as an action effect. Piloting revealed that the mean individual RT2+ 50 ms would fulfill both criteria reasonably well, and we thus used this delay in this Experiment. Participants first worked through a PRP experiment where responses produced immediate visual effects (cf. Fig. 1). Based on the RTs collected in this phase, the effect of the first response was delayed in the second phase of the experiment. Our prediction was that this effect delay would increase RT2.

Methods

Participant

Sixteen undergraduate students of the Dortmund University of Technology received either course credit or 3€ as a compensation for their participation. All participants reported normal vision and hearing. They were naïve concerning the hypotheses of the experiment and provided signed informed consent. Part of the data for one participant was lost and the subsequent analyses are based on the remaining 15 participants.

Apparatus and stimuli

The experimental protocol was controlled by a standard PC attached to a 17-inch CRT monitor. Stimuli for Task 1 (S1) were sinusoidal tones (300 and 900 Hz) presented for 50 ms via headphones. Stimuli for Task 2 (S2) were the letters H and S presented centrally in white color against a black background. Responses were collected via four custom-built response keys attached to the parallel port. Two of the response keys were located on the left side of the participant for the Task 1 response (R1), the other two on the right side for the Task 2 response (R2). The visual effects in both tasks (E1 and E2, respectively) were white-filled circles presented to the left (E1) or to the right (E2) of the screen center.

Tasks and procedure

Task 1 was to respond with the left index or middle finger according to S1 pitch, and Task 2 was to respond with the right index or middle finger according to S2 letter identity. For the following procedural description, please see also Fig. 1. Each trial started with a white fixation cross (250 ms) followed by a blank screen (250 ms). Then, S1 was played and following an SOA of 50 or 1000 ms, S2 was displayed on the screen (for 500 ms or until R2). Pressing a response key with the left hand (i.e., giving R1) triggered the presentation of E1 for 500 ms. Importantly, however, the exact onset varied according to a critical manipulation: In “immediate E1” blocks, E1 set on immediately when giving R1. In “delayed E1” blocks in contrast, E1 set on only after a specific delay (see below for how the delay was determined). Pressing a response key with the right hand (i.e., giving R2) triggered the immediate onset of E2 for 500 ms. Accuracy feedback (correct or error responses) was provided during the inter-trial interval of 2000 ms.

Each block consisted of seven repetitions of the eight trial types resulting from the orthogonal combinations of 2 S1 (300 vs. 900 Hz) × 2 S2 (H vs. S) × 2 SOAs (50 vs. 1000 ms). Within blocks, trials were presented in random order. Following a written instruction, participants started with two practice blocks (Blocks 1–2), which were followed by four blocks with immediate E1 onset (without delay; Blocks 3–6) and four blocks with delay (Blocks 7–10). The instructions for participants were as follows: “In this experiment you should work on two tasks concurrently. In Task 1 you are asked to decide as quickly as possible, if a tone is low or high. In Task 2 you are asked to decide if in the middle of the screen the letter H or the letter S is presented. For Task 1 you should use the index and middle finger of the left hand, and for Task 2 you should use index and middle finger of the right hand. You will hear the tone for Task 1 first, and then the letter for Task 2 appears. The time in between varies randomly”. The E1 delay was calculated as the mean of the correct RT2 between 300 and 3000 ms in Blocks 3–6 plus 50 ms (i.e., the short SOA). Stimulus–response mappings of both tasks were counterbalanced across participants.

Table 1 Mean percentages of trials in Experiment 1 where E1 occurred before E2 (E1 → E2) and where E2 occurred before E1 (E2 → E1) as a function of SOA and E1 delay

	Without E1 delay		With E1 delay	
	E1 → E2	E2 → E1	E1 → E2	E2 → E1
SOA = 50	96.2	3.8	3.8	96.2
SOA = 1000	99.6	0.4	58.1	41.9

Data treatment

Trials with RTs higher than 4000 ms were excluded as were trials with general errors (two responses for Task 1, response prior to stimulus onset). For RT analyses, only entirely correct trials were considered, and trials with RTs deviating from the mean RTs for more than 2.5 SDs were excluded as outliers (calculated separately for each design cell and participant). Mean RTs and mean percentages error (PE) were analyzed with Analyses of Variance with SOA (50 vs. 1000 ms) and effect delay (without vs. with) as repeated measures.

Results

We first computed the percentages of trials in which the effects occurred in the order E1 → E2 and reversed as E2 → E1 as a function of SOA and E1 delay (cf. Table 1). This analysis will become relevant when discussing the results in terms of alternative interpretations later.

Task 1

Mean correct RT1 (2.68% outliers) are visualized in Fig. 3. No effect was significant in the analysis of RT1 s, all $F\text{s} \leq 2.42$, all $p \geq 0.142$. Mean error percentages are summarized in Table 2. Participants made more errors with a short SOA, $F(1,14) = 11.61$, $p = 0.004$, $\eta_p^2 = 0.45$. No other effect was significant, all $F\text{s} \leq 1.27$, all $p \geq 0.279$.

Task 2

Mean correct RT2 (2.99% outliers) are visualized in Fig. 3. Participants responded slower with a short SOA ($M = 1022$ ms) as compared to a long SOA ($M = 574$ ms), thus a PRP effect, $F(1,14) = 178.41, p < 0.001, \eta_p^2 = 0.93$. They also responded faster with immediate ($M = 783$ ms) than with delayed effects ($M = 813$ ms), $F(1,14) = 4.84$, $p = 0.045$, $\eta_p^2 = 0.26$. The interaction was not significant, $F(1,14) = 0.13$, $p = 0.726$, $\eta_p^2 = 0.01$. Mean error percentages are summarized in Table 2. More errors were committed with a short compared with a long SOA, although the main effect of SOA was not quite significant, $F(1,14) = 3.67$, $p = 0.076$, $\eta_p^2 = 0.21$. In addition, more errors were committed with an immediate effect compared to delayed effects, $F(1,14) = 6.81$, $p = 0.021$, $\eta_p^2 = 0.33$.

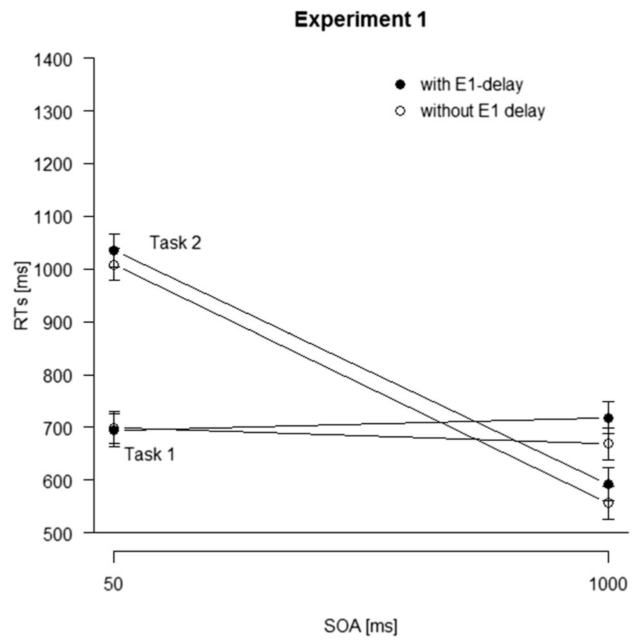

Fig. 3 Response times (RTs) of Tasks 1 and 2 as a function of task, stimulus onset asynchrony (SOA), and effect delay in Experiment 1. *Error bars* are 95% within-subject confidence intervals of the difference between no-delay and delay conditions, calculated separately for each task and collapsed across SOAs (Pfister & Janczyk, 2013)

The interaction was not significant, $F(1,14) = 0.91$, $p = 0.356$, $\eta_p^2 = 0.06$.

Discussion

Experiment 1 revealed an important finding: delaying the visual feedback of the responses of a first task delays the responding in a secondary task. We assume that this originates from the still ongoing monitoring of the upcoming visual effect during the response-effect interval which interferes with the processing of a second task, most likely with the selection of the second response.

Some possible alternative explanations of this observation can already be deemed unlikely. First, it is unlikely that the pure occurrence of a visual event (the effect of R1) interfered with Task 2 processing. If this were so, there should be a larger impact of effect delay with a long SOA as compared to a short SOA because there were more cases in which E1 preceded E2/R2 in the former case as compared to the latter (cf. Table 1). However, statistically the impact of

Table 2 Mean error percentages in Experiment 1 and 2 as a function of task, stimulus onset asynchrony, and effect delay

Task	SOA	Experiment 1		Experiment 2	
		Without E1 delay	With E1 delay	Without E1 delay	With E1 delay
1	50	3.9	2.7	3.9	4.1
	1000	0.9	1.0	1.4	1.2
2	50	4.6	3.0	3.7	4.6
	1000	2.4	1.8	4.5	4.2

effect delay was of similar size for both SOAs. Second, for the same reason it is also unlikely that, conversely, the presentation of E1 caused some kind of unspecific speeding up of R2. Again, if this were so, there should be a bigger RT2 facilitation at the 1000 ms SOA than at the 50 ms SOA, because there were more cases with E1 preceding R2 in the former than in the latter. Thus, rather than processing of the actual effect, the waiting period prior to this effect (i.e., monitoring) seems to be more relevant here.

However, we did not counterbalance the order of the conditions with and without delay. The condition with delay was always second. It seems thus tenable that the increase of RT2 was due to unspecific fatigue, or perhaps surprise about the sudden introduction of the E1 delay. In addition, this account seems not very likely, because there were no significant differences between conditions in RT1, which should be the case if unspecific fatigue or surprise was involved. However, there was, at least at a descriptive level, an increase in RT1 with delayed effects at the long SOA (which, however, went along with a slight decrease with immediate effects). This account certainly deserved closer examination in Experiment 2. Finally, the data exhibited a slight speed–accuracy tradeoff in Task 2 results. Thus, although we believe that the results go into the right direction, a clear-cut interpretation is further complicated and we will await the results obtained with Experiment 2.

Experiment 2

Experiment 2 is basically a replication of Experiment 1 with two modifications. First, the condition with delayed E1 was now encountered first, and the condition without delay came second. This was done to test whether the increase of RT2 with delayed effects was due to fatigue or surprise. Second, we used the same E1 delay for all participants based on the delays obtained in Experiment 1, to test whether the results would also replicate with a more simplified (and more practical) manipulation of delays.

Methods

Participants

A new sample of 16 undergraduate students of the Dortmund University of Technology participated for the same criteria as in Experiment 1.

Apparatus, stimuli, procedure, and data treatment

In most aspects, Experiment 2 followed Experiment 1 with only few changes. The most important change relates to the fact that now Blocks 3–6 were those with a delayed effect, and Blocks 7–10 were those without delay. The delay was the same for all participants in this case and we used the mean of the (individual) delays obtained from the 16 original participants of Experiment 1 (885 ms).

Results

We again analyzed in how many cases E1 occurred prior to E2/R2 depending on SOA and E1 delay, and the resulting percentages are summarized in Table 3.

Task 1

Mean correct RT1 (2.92% outliers) are visualized in Fig. 4. No effect was significant, all Fs ≤ 0.47, all $p \geq 0.503$. Mean error percentages are summarized in Table 2. Participants made more errors with a short SOA, $F(1,15) = 20.62$, $p < 0.001$, $\eta_p^2 = 0.58$. No other effect was significant, all Fs ≤ 0.43, all $p \geq 0.524$.

Task 2

Mean correct RT2 (2.51% outliers) are visualized in Fig. 4. Participants responded slower with a short SOA ($M = 1241$ ms) as compared to a long SOA ($M = 720$ ms), thus a PRP effect, $F(1,15) = 211.70$, $p < 0.001$, $\eta_p^2 = 0.93$. They also responded faster with immediate ($M = 922$ ms) than with delayed effects ($M = 1039$ ms), $F(1,15) = 8.01$, $p = 0.013$, $\eta_p^2 = 0.35$.

Table 3 Mean percentages of trials in Experiment 2 where E1 occurred before E2 (E1 → E2) and where E2 occurred before E1 (E2 → E1) as a function of SOA and E1 delay

	Without E1 delay		With E1 delay	
	E1 → E2	E2 → E1	E1 → E2	E2 → E1
SOA = 50	88.9	11.1	7.5	92.5
SOA = 1000	92.3	7.7	54.4	45.7

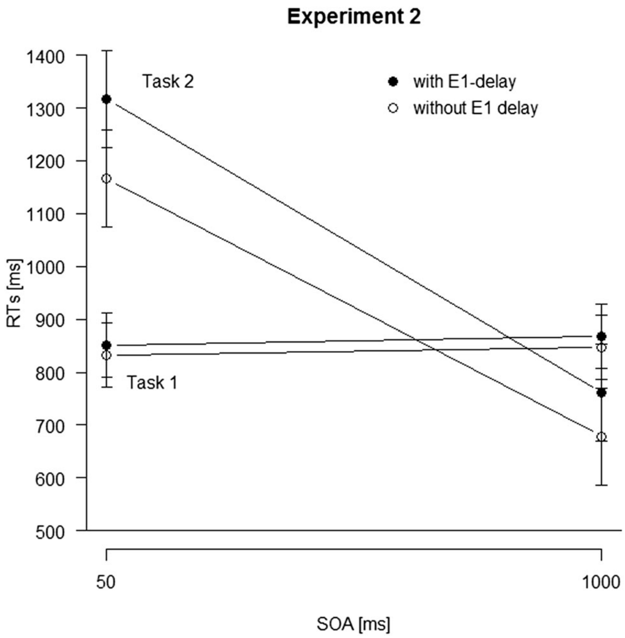

Fig. 4 Response times (RTs) of Tasks 1 and 2 as a function of task, stimulus onset asynchrony (SOA), and effect delay in Experiment 2. *Error bars* are 95% within-subject confidence intervals of the difference between no-delay and delay conditions, calculated separately for each task and collapsed across SOAs (Pfister & Janczyk, 2013)

This latter difference was more pronounced with a short SOA ($\Delta = 150$ ms, $t(15) = 3.15$, $p = 0.007$, $d = 1.12$) as compared to a long SOA ($\Delta = 83$ ms, $t(15) = 2.17$, $p = 0.046$, $d = 0.77$), yielding a significant interaction between SOA and effect delay, $F(1,15) = 6.82$, $p = 0.020$, $\eta_p^2 = 0.31$. Mean percentages are summarized in Table 2. Descriptively, more errors occurred with a delayed than with an immediate effect with a short SOA, but this difference was reversed (and smaller) with a long SOA, and the interaction approached significance, $F(1,15) = 3.74$, $p = 0.072$, $\eta_p^2 = 0.20$. No other effect was significant, all Fs ≤ 0.23, all $p \geq 0.638$.

Discussion

The results of Experiment 2 basically replicate those of Experiment 1. Again, delaying the effects of the first of two responses in a PRP paradigm delayed responses in a second task. This effect occurred despite now conducting the condition with effect delay first, and the condition without effect delay second. This renders explanations in terms of fatigue or surprise unlikely, as does the specificity of the impact of effect delay on RT2 (but not RT1).

The influence of effect delay on RT2 was somewhat larger in Experiment 2 as compared to Experiment 1 (though not significantly so[1]). Moreover, the influence of effect delay was more pronounced with the short rather than the long SOA in Experiment 2. The causes for this are not entirely clear. Response times in Experiment 2 were overall somewhat longer than in Experiment 1, which probably goes along with longer response selection processes as well. This might increase the periods of potential sharing of capacities, particularly with delayed E1 at the short SOA, where response selection in Task 2 likely overlaps with both, monitoring of Effect 1 and selection of Response 1. This speculation certainly requires further empirical testing.

General discussion

The present two experiments set out from the idea that humans monitor what they do. That is, they try to keep track of the sensory effects they produce with their motor actions. The reasons for doing so are multiple, such as checking whether intended effects were achieved, or whether systematic contingencies between own motor activities and sensory changes in the environment emerge.

The more specific question we asked here is whether such self-observation of what we do contributes to the problems of doing two things at once. To test that, we delayed the visual effects of the first of two overlapping actions, with the idea that this would lengthen the time period in which the monitoring of the upcoming action feedback is engaged. If such monitoring required central capacity, less of this capacity should be available for processing a concurrent task, which should consequently take longer to complete. This is what we observed. Hence, we believe that monitoring of action effects is a source of dual-task costs on its own. We now turn to the theoretical implications of this outcome and lines for future research.

Why effect monitoring?

As noted before there are generally good reasons to keep track of what we cause. The present study suggests that this is true even for events that are nominally task-irrelevant, as were the effects in the present study. That is, the effects were not needed to carry out the tasks correctly, and this

[1] *A between experiments ANOVA for RT2 with the factors SOA, effect delay and experiment revealed significant effects of the factors SOA* $F(1,29) = 377.98$, $p < 0.001$, $\eta_p^2 = 0.93$, *effect delay,* $F(1,29) = 14.54$, $p = 0.001$, $\eta_p^2 = 0.33$, *and experiment,* $F(1,29) = 5.09$, $p = 0.031$, $\eta_p^2 = 0.15$. *The interaction of experiment and effect delay missed conventional levels of significance* $F(1,29) = 3.59$, $p = 0.068$, $\eta_p^2 = 0.11$, *and so did the triple interaction of all three main effects* $F(1,29) = 3.03$, $p = 0.092$, $\eta_p^2 = 0.09$.

corresponds to observations showing that people do attend to what they cause, even events not necessarily needed for a given task (Band et al., 2009; Dutzi & Hommel, 2009; Moeller, Pfister, Kunde, & Frings, 2016), In fact, one may wonder if every sudden stimulation deteriorated another task, be it an action effect or not. This might be so. But please note, even if this was so, performers do inevitably produce such stimulation in temporally overlapping tasks, let it only be tactile feedback from responding fingers. Thus, such self-stimulation does shape dual-task performance—a point that has not received much attention in dual-task research so far (but see Welford, 1952). However, it is certainly important to check whether the costs of processing such stimulation increase when the sensory effects become more task-relevant.

In addition, the burdens of effect monitoring, and the processes it affects, might depend on the overlap of sensory modalities of Task 1 effects and Task 2 stimuli. These were both visual in the present study and it will be of particular interest to explore whether monitoring effects diminish when the modalities of these events are different. Finally, monitoring costs might increase with decreasing naturalness of feedback. For example, monitoring the rather unusual visual feedback of an object occurring after a finger movement might pose higher demands than monitoring the more familiar tactile feedback from the finger hitting a response key. Likewise monitoring visual feedback might pose higher demands when being spatially incompatible rather than compatible to the action (Wirth, Janczyk, & Kunde, 2016).

With which processes does monitoring interfere?

While we did show that delaying action effects modulates processing of another task, we did not directly demonstrate at which specific processing stage this modulation occurs. Actually, we conjecture that are multiple causes for such delay. First, as shown in Fig. 2, it seems possible that longer monitoring of a delayed effect interferes longer with the selection of a concurrently required response. Second, it might also be that the overlap of two effect monitoring processes causes some additional delay. Possibly the initiation of motor output starts only when sufficient capacity for monitoring its sensory feedback is available. With overlap of two monitoring processes, more time might be needed until sufficient capacity is available to monitor the effect of the second response, causing this response to be initiated later. Third, strategic processes specific to the PRP paradigm might come into play. Typically, participants prefer to respond in the order of the stimuli, thus R1 before R2, for example, to avoid switching between tasks back and forth (Meyer & Kieras, 1997). Delayed feedback moves the perceived time point of the response towards the time point of the feedback (Haggard, Clark, & Kalogeras, 2002). It will, therefore, be harder to detect that R2 occurred after R1 when the feedback of R1 is delayed. Consequently, participants might intentionally delay R2 to be sure that it actually occurs after R1, or they might be reluctant to execute R2 before the last element of Task 1 (i.e., E1) had been perceived, though they could overcome such hesitation in principle.

Still another possibility has emerged from studies in which the stimulus for the second task appears always slightly after the effects of a first task. This situation is more similar to task switching rather than to the PRP situation studied here. Interestingly, in such a more sequential task order, Task 2 does not seem to start at all before monitoring of previous response effects has been more or less completed (Wirth, Janczyk, & Kunde, 2016). Perhaps the stronger overlap between tasks induced in the present PRP study induces also more simultaneity of effect monitoring processes as compared to situations with a more sequential order of tasks as in task switching.

Note that a serial bottleneck model might be accommodated with the present data as well. The serial model assumes that resources cannot be shared between effect monitoring in Task 1 and response selection in Task 2, but that one of these processes would occupy the bottleneck first and as long as this process was completed (Pashler, 1994). To explain the RT increase in Task 2, we would have to assume that with delayed effects in Task 1 the probability increases that response selection in Task 2 calls for the bottleneck process while monitoring of Effect 1 is still going on. Obviously, the question which processes effect monitoring does affect in concurrent tasks depending on temporal overlap awaits more fine-grained future research.

Why no effects on Task 1?

While the manipulation of E1 delay had a noticeable influence of RT2, it had essentially no influence on RT1, except descriptively at the long SOA of Experiment 1. On the one hand, this helps ruling out unspecific explanations in terms of fatigue or surprise. However, on the other hand, foreseeably delayed effects have been shown to increase response times under appropriate conditions (Dignath et al., 2014, Dignath & Janczyk, 2016). But note, the main difference between these studies and the present one is that the effect delay was much larger (about 2000 ms) in the former than in the latter (about 900 ms). It should be tested whether this or other differences such as the dual-task context prevented the typical RT increase with foreseeably delayed effects to manifest.

The bigger picture: the role of action effects in dual tasking

We show here that monitoring sensory effects determines dual-task performance. However, action effects shape dual-task performance in other ways as well. First, motor actions might in general be stored and retrieved by memories of their sensory consequences. Thus, it is the recollection of an action effect, that is, its mental anticipation that selects the corresponding motor pattern and may pose a bottleneck (e.g., Harleß, 1861; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Janczyk, Durst, & Ulrich, 2016; Janczyk & Kunde, 2014; Kunde, 2001; Kunde, Elsner & Kiesel, 2007). In fact, the anticipation of action effects seems to take place at a point in time when the response selection bottleneck stage in information processing is assumed to occur (Paelecke & Kunde, 2007; Wirth, Pfister, Janczyk, & Kunde, 2015). Several further observations suggest that action effects (and their anticipation) play a crucial role in producing dual-task costs (see Janczyk, 2016a, for an overview). For example, two motor actions are more easily produced simultaneously if they result in similar rather than dissimilar action effects (Janczyk, Skirde, Weigelt, & Kunde, 2009). Moreover, the reconcilability of two specific tasks, such as mentally and manually rotating an object, is determined by the intended sensory effects of the manual action, not by the efferent output per se (Janczyk, Pfister, Crognale, & Kunde, 2012). Finally, action effects also determine the size of the so-called backward crosstalk effects (Hommel, 1998; Janczyk, 2016b) in dual-task situations (Janczyk, Pfister, Hommel, & Kunde, 2014). The interplay of these effect-oriented processes, such as anticipation, maintenance, and monitoring of action effects deserves further research and theoretical integration.

The present study suggests that effect monitoring can pose still another constraint on multitasking on top of those already previously discussed such as the selection of responses (Welford, 1952). However, our study does not suggest that these limitations are insurmountable, but rather we suggest a considerable degree of flexibility of such monitoring. First, the model shown in Fig. 2 already implies that more or less capacity might be devoted to effect monitoring and other tasks, depending on effect relevance or strategic factors. Second, participants can likely use various sensory feedback signals to monitor what they did, providing these signals are redundant, such as tactile and visual feedback. So possibly there are conditions in which participants completely ignore the visual feedback that we manipulated here, and prefer to rely on tactile feedback from the responses alone. If they did so, it will not matter whether visual feedback is delayed or not. Third, it might be possible to schedule monitoring processes also in time, in such a way that monitoring is engaged when feedback signals are likely, and disengaged when they are unlikely. Consider a situation in which there is a foreseeably long interval between actions and effects, such as when switching on an old PC and waiting for the login screen of the operating system. With such a long waiting interval, it would be counterproductive to devote a lot of capacity to effect monitoring during the waiting period itself, because other tasks (such as making a brief phone call) might completely fit into the waiting period, providing sufficient capacity for these tasks was spared. As a rough estimate, with everything else being equal, less capacity should be devoted to effect monitoring the longer the monitoring interval. Basically, such temporal disengagement from effect monitoring with later engagement might occur in tasks like those used here as well, when feedback delays get even longer.

Conclusion

Doing two things at once is hard, and there are multiple causes for this. We believe, and argue to have shown that one so far neglected cause is the monitoring of action feedback that does not easily combine with processing other concurrent tasks. This was demonstrated here in one standard dual-task paradigm. Whether this holds true for other cases of multitasking such as dual-tasking proper, or task switching, is a question open for empirical examination.

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