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Evidence for Initially Independent Monitoring of Responses and Response Effects

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To act successfully, agents must monitor whether their behavior reached predicted effects. As deviations from predicted effects can result from own behavior (response-errors) or from circumstantial unreliability (effect-errors), both the own efferent activities and the accomplished environmental outcomes must be monitored. In three experiments, we examined response monitoring and effect monitoring using a dual-task setup. Task 1 consisted of a three-choice flanker task and effects were displayed after the response. Crucially, in some of the trials, an incorrect effect was displayed after a correct response, whereas in other trials, a correct effect was displayed after an incorrect response. This disentangled response-errors and effect-errors. Task 2 was a simple discrimination task and served to measure the monitoring process. Task 2 responses slowed down after both response-errors and effect-errors in Task 1. These influences were additive, suggesting two independent monitoring processes: one for responses, capturing errors in efferent activities, and one for response effects, checking for environment-related irregularities.

Public Significance Statement
Humans monitor whether they achieved certain effects, and how they achieved them. Here, we provide evidence that response-errors resulting in effect-errors take longer to monitor than response-errors resulting in correct effects. We conclude that the anticipation of environmental response effects is initially independent of the actual, executed response.

Keywords: error monitoring, effect monitoring, cognitive control, psychological refractory period

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Humans change their perceptions by their actions. They attempt to produce specific effects in the environment through certain motor behavior. Goal-directed actions thus consist of two components: *what* to do (the intended effect) and *how* to do it (the required efferent activity). Failures can occur at both levels. Either the how-component fails, because an inappropriate motor action is chosen, and/or the what-component fails, because disturbances in the environment obstruct the desired effect. Imagine wanting to turn on the light when entering a dark room. You may fail to do so, either because you pressed the wrong switch ("response-error"), and/or because the light bulb is broken ("effect-error"). Consequently, agents must monitor what they achieved, as well as how they achieved it.[1]

When humans commit errors, their consecutive actions are typically slowed down (Laming, 1979; Rabbitt, 1966; Steinhauser et al., 2008). This slowdown is to some extent due to prolonged monitoring of what went wrong. Such slowing occurs not only after response-errors, that is, when an inappropriate response alternative has been chosen (Dudschig & Jentzsch, 2009; Steinhauser et al., 2017), but also after effect-errors, that is, when the environment does not provide the intended perceptual change (Houtman & Notebaert, 2013; Pfister et al., 2020; Weller et al., 2018). To illustrate this monitoring of effect-errors, consider a recent dual-tasking study (Wirth, Janczyk, & Kunde, 2018): In Task 1, participants were instructed to produce an object on a screen by pressing a key. Shortly after the onset of this visual action effect, the imperative stimulus for Task 2 was displayed. The timing of the second stimulus depended on the participants' response (RSOA: response-stimulus onset asynchrony), which allowed us to pinpoint systematic variations in the performance of Task 2 to the still ongoing monitoring of the Task 1 action effects (see Figure 1). Task 1 responses occasionally produced effects that were associated with the alternative response (i.e., a key that produced a certain action effect in 75% of the trials produced an unexpected action effect in 25% of the trials). This expectancy violation affected Task 2 performance, evidently due to prolonged monitoring of this effect (Kunde et al., 2018; Wirth & Kunde, 2020).

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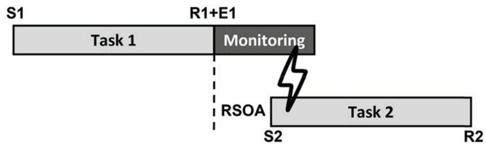
[1] In contrast to error feedback, effect-errors are conditional on the intended effect: A dark room after pressing a wrong switch is accurate feedback, but an effect-error.

Figure 1
Experimental Logic



Note. The model assumes that prolonged Task 1 monitoring increases Task 2 reaction times if the response-stimulus onset asynchrony (RSOA) is short enough.

In the present study, we investigated the relationship of those monitoring costs for response-errors and effect-errors. As discussed above, incorrectly chosen responses (response-errors) as well as false action effects (effect-errors) prolong monitoring, compared with conditions where an appropriately chosen action produces an intended effect. The intriguing question is how monitoring of response-errors is connected to monitoring of effect-errors. To answer this, we had a stimulus prompt two requirements: which response to carry out, and which effect to produce. This allowed to assess four conditions: A correct response could result in either the originally suggested effect ("Success") or in an effect-error ("Insertion"). Conversely, a response-error could result in the suggested effect ("Correction") or in an effect-error ("Mistake").

Existing literature leads to diverging predictions on the monitoring duration of these conditions. The expectation of an action effect could be based on the actual, executed response, not the intended response in a given situation (Oliveira et al., 2007; Wessel, 2018). If this was the case, Corrections should be monitored longer than Mistakes, as it is unexpected that response-errors produce the effect which the correct response usually produces.

Alternatively, monitoring of response-errors and effect-errors could operate independently of each other. Logan and Crump (2010) report that only response-errors (but not effect-errors) slow down consecutive actions, while only effect-errors (but not response-errors) get noticed on the explicit level of self-report. Although the lack of slowdown after effect-errors is inconsistent with recent studies (Lavro & Berger, 2015; Saunders & Jentzsch, 2012), the selective influence of response-errors and effect-errors on different dependent variables suggests some degree of disconnection. Assuming such independency would entail that effect monitoring does not exchange any information with response monitoring. Therefore, we hypothesized that the anticipated effect is determined by (and evaluated against) the intended response (based on the imperative stimulus) rather than the executed response. Thus, independent monitoring of response-errors and effect-errors should be reflected as additive influences on the same dependent variable. In a nutshell, if responses and response effects were monitored independently, effect expectancy could not be based on the executed response, and Mistakes should be monitored longer than Corrections. Specifically, a Mistake should have the combined impact of an erroneous response (Correction) and an unexpected action effect (Insertion).

Experiment 1

The first experiment aimed at revealing distinguishable monitoring for responses and response effects (Logan & Crump, 2010). For Task 1, participants were instructed to produce an action effect by responding to a stimulus. A three-choice flanker task with only incongruent flankers (Eriksen & Eriksen, 1974; adapted from Steinhauser et al., 2018) ensured a sufficient rate of response-errors. In 25% of the trials, an unexpected action effect (effect-error) was displayed.

Task 2 served to measure the ongoing monitoring processes of Task 1, with longer monitoring of Task 1 resulting in higher response times to Task 2 (e.g., Wirth, Janczyk, & Kunde, 2018; see Figure 1). We assumed that response-errors in Task 1 lead to a prolongation of the monitoring process (Jentzsch & Dudschig, 2009). We likewise assumed that effect-errors prolong the monitoring process (Houtman & Notebaert, 2013). Crucially, if monitoring of response-errors and effect-errors is indeed operating independently, the influences of incorrect responses and unexpected effects should be additive.

Method

Participants

We based our power calculation for the monitoring of effect-errors on the expectancy effect Wirth, Steinhauser, et al. (2018) obtained (Experiment 1, high-compatibility condition, $d_z = .55$ or $\eta^2 = .07$). While 46 participants would suffice to uncover this effect at an alpha of .05 and power of .95 (Anderson & Kelley, 2020), we opted to recruit 48 participants because it allowed for counterbalancing of the S-R mappings. For the final sample (37 females, $M_{age} = 22.2$ years, $SD = 2.5$), 13 participants were replaced due to high (nine participants) or low (four participants) error rates (see Appendix A for the pilot study, and Appendix B for a discussion of the rejection criteria). All participants provided written informed consent and received monetary compensation.

Apparatus and Stimuli

For Task 1, stimuli were three colored squares at the bottom of the screen (S1; see Figure 2). The outer two squares (flankers) were of the same color and always incongruent to the middle square (target). Displaying the flankers before the target further increased the difficulty of Task 1 and provoked errors. The color of the target square (red vs. green vs. blue) required a left-hand response (R1) on the "A", "S", or "D" keys of a QWERTZ keyboard. This response to Task 1 made a centrally presented gray lightbulb change its color as action effect (E1; red vs. green vs. blue). In 75% of the trials, E1 matched the color of the target, while in the remaining 25%, E1 was the color appearing in neither target nor flankers. Crucially, while the timing of E1 was dependent on R1, the color of E1 was dependent on S1 and thus detached from the identity of R1.

For Task 2, participants had to respond to a letter (S2; "S" vs. "H") displayed in white font within E1 by pressing either the "N" or "M" key with their right hand (R2). The S-R mapping for both tasks was counterbalanced between participants. Before the experiment started, participants received the instructions to turn on the lightbulb in the color of the central square (see Appendix D Table D1 for the full instructions).

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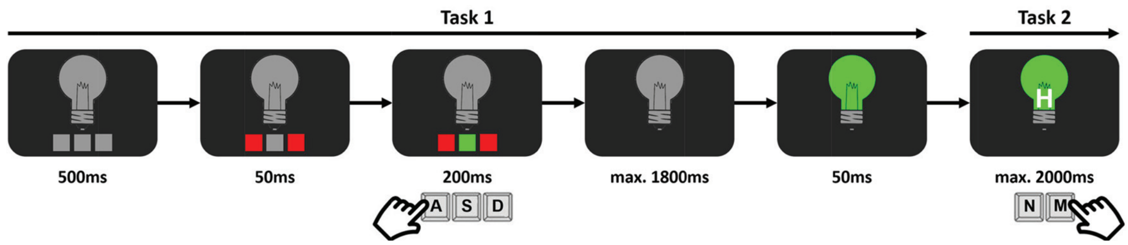
Figure 2
Trial Procedure Used in the Experiments



Note. For Task 1, participants responded to the color of the middle square by pressing either the A, S, or D key. This response filled a gray lightbulb with an expected or unexpected color. After this action effect, a white letter appeared in midst of the lightbulb to which participants had to respond with the N or M key (Task 2). See the online article for the color version of this figure.

Procedure

A gray lightbulb and three gray squares marked the beginning of a trial. After 500 ms, the color of the S1 flankers was presented. The S1 target color was presented 50 ms after flanker onset, and target and flankers stayed on screen for 200 ms. If no R1 was given within 2,000 ms, the trial counted as omission and the lightbulb remained gray. Otherwise, E1 appeared immediately after R1 and stayed on screen until the trial ended.

Fifty milliseconds after E1, S2 was presented and called for R2. The next trial started immediately after R2. Again, if no R2 was given within 2,000 ms, the trial counted as an omission. The two tasks were always presented in this order with no temporal overlap (except for the display of E1) between the tasks. Neither for Task 1 nor for Task 2 direct feedback regarding errors was provided.

In between blocks, participants were reminded of the S-R mappings and were encouraged to react faster or more accurate, depending on their error rates in Task 1. Participants completed 20 blocks consisting of 48 trials; each of the 12 possible combinations of S1 (Three Targets × Two Distractors) and S2 (two letters) was displayed three times for expected and one time for unexpected E1s.

Results

Analysis code and raw data for all experiments are publicly available at the Open Science Framework (osf.io/96ja4). The first block was considered a training block and excluded from all analyses. For response time (RT) analyses, trials with omissions in Task 1 (0.9%) or errors (including omissions) in Task 2 (10.8%) were removed. No further data was excluded. The final sample for RT analyses consisted of 88.6% of the original trials. For the analysis of error rates, trials with omissions in Task 1 were excluded. Data were analyzed with 2 × 2 analyses of variance (ANOVAs) with R1 accuracy (correct vs. incorrect) and E1 expectancy (expected vs. unexpected) as within-subjects factors (see Figure 3). Additionally, evidence for the absence of an interaction in Task 2 RTs was quantified by a Bayesian follow-up analysis using the R package BayesFactor (Morey & Rouder, 2018) with a Cauchy scale parameter of 1.

Task 1 RTs

No influences on Task 1 RTs were observed, all Fs < 3.26, all ps $> .077$.

Task 1 Error Rates

Participants committed an average of 11.6% (SD = 5.0%) Task 1 errors.

Task 2 RTs

Task 2 RTs were lower after a correct R1 (514 ms) than after an incorrect R1 (620 ms), $F(1, 47) = 60.16$, $p < .001$, $\eta_p^2 = .56$. Further, Task 2 responses were faster after an expected E1 (552 ms) than after an unexpected E1 (582 ms), $F(1, 47) = 11.67$, $p = .001$, $\eta_p^2 = .20$. Crucially, there was no interaction between R1 accuracy and E1 expectancy, $F(1, 47) = 0.20$, $p = .655$, $\eta_p^2 < .01$, BF_{10} = 0.11 (BF_{01} = 8.90).

Task 2 Error Rates

There were more Task 2 errors after an incorrect R1 (21.5%) than after a correct R1 (9.5%), $F(1, 47) = 65.14$, $p < .001$, η_p^2 = .58. All other Fs < 1.

Discussion

In Experiment 1, we instructed participants to produce a certain action effect via a certain response. However, the identity of this action effect was independent of the participants' response, allowing to separately assess violations of the required response and the required response effect. The obtained results show that response times and error rates of the unrelated Task 2 depend largely on still ongoing monitoring processes of Task 1. Not only response-errors, but also effect-errors decreased subsequent performance. Crucially, these influences were additive, suggesting monitoring systems that operate independently of each other.

Experiment 2

While the effect of Task 1 did not convey any information about the correctness of the participants' response and had no obvious benefit for the task, the instructions of Experiment 1 explicitly stated that participants should try to produce a certain effect. Hence, participants may have seen it as part of the explicit task requirements to monitor whether they produced this action effect with their response. The aim of Experiment 2 was to examine whether the instructions to produce E1 were causal for the slowdown in Task 2 after unexpected effects. To put less emphasis on the R1-E1 relationship, participants were now only instructed to

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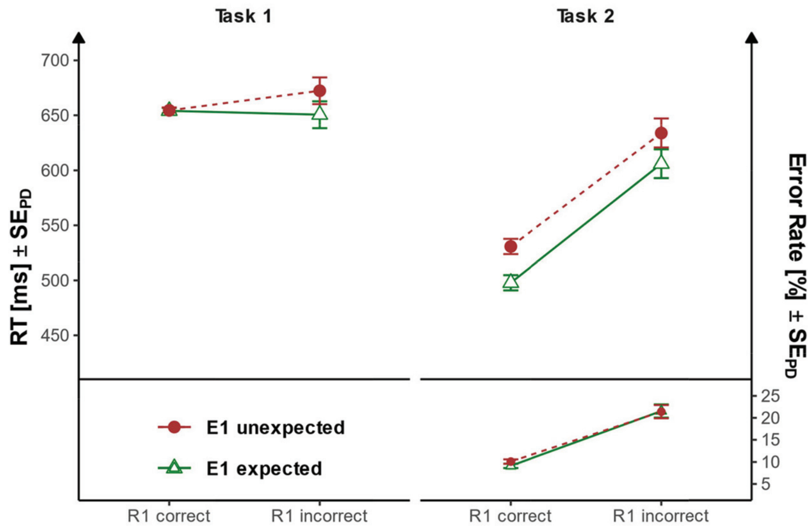
Figure 3
Results of Experiment 1



Note. Response times (RTs; top) and error rates (bottom) for Task 1 (left) and Task 2 (right). Green triangles represent trials with expected effects, whereas red points represent trials with unexpected effects. Error bars denote the standard error of paired differences, computed separately for each comparison of expectedness (Pfister & Janczyk, 2013). See the online article for the color version of this figure.

respond to the colored squares. As previous research suggests that action effects are monitored irrespective of their relevance (Band et al., 2009; Notebaert et al., 2009), we expected the results of Experiment 1 to replicate in this setting.

Method

Forty-eight new participants (33 females, M_{age} = 23.5 years, *SD* = 3.6) were recruited. This ensures a power of >.90 at an alpha of .05 to detect monitoring of effect-errors, assuming an effect size as observed in Experiment 1. Sixteen participants were replaced due to high (five participants) or low (11 participants) error rates (see Appendix B). Apparatus, stimuli, and procedure were exactly as in Experiment 1, but the instructions now told participants to respond to the colored squares and did not mention the ensuing action effect (see Appendix D Table D1 for the full instructions).

Results

Data were treated and analyzed as in Experiment 1 (see Figure 4). After excluding Task 1 omissions (0.7%) and Task 2 errors (9.1%), the sample for RT analyses consisted of 90.3% of the original trials.

Task 1 RTs

No influences on Task 1 RTs were observed, all *F*s < 1.35, all *p*s > .252.

Task 1 Error Rates

Participants committed an average of 10.6% (*SD* = 5.1%) Task 1 errors.

Task 2 RTs

Task 2 RTs were lower after a correct R1 (462 ms) than after an incorrect R1 (596 ms), $F(1, 47) = 66.73$, $p < .001$, $\eta_p^2 = .59$. Further, Task 2 responses were faster after an expected E1 (519 ms) than after an unexpected E1 (539 ms), $F(1, 47) = 15.19$, $p < .001$, $\eta_p^2 = .24$. Again, there was no interaction between R1 accuracy and E1 expectancy, $F(1, 47) = 0.33$, $p = .568$, $\eta_p^2 = .01$, BF_{10} = 0.11 (BF_{01} = 8.88).

Task 2 Error Rates

Task 2 error rates were higher after an incorrect R1 (17.1%) than after a correct R1 (8.0%), $F(1, 47) = 65.96$, $p < .001$, η_p^2 = .58. All other *F*s < 1.

Discussion

The results of Experiment 2 closely replicate those of Experiment 1. Albeit the action effect was nominally irrelevant and not mentioned in the instructions, responses and response effects of Task 1 were monitored and resulted in Task 2 performance decreases. Again, these influences were additive. This suggests that the observed monitoring is not limited to goal-relevant effects.

Experiment 3

The results of Experiment 1 and 2 suggest that participants monitor whether their expectancy, evoked by the intended response (based on the imperative stimulus), matches the produced response effects. Yet, E1s were not only contingent on S1s, but also resembled them on a perceptual level (e.g., a green S1 target came most often with a green E1, cf. Figure 2). This renders it

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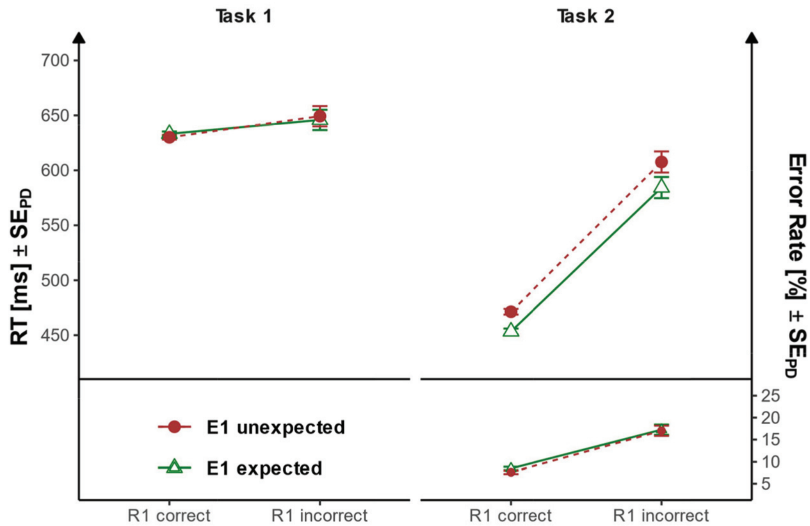
Figure 4
Results of Experiment 2



Note. Response times (RTs; top) and error rates (bottom) for Task 1 (left) and Task 2 (right). Green triangles represent trials with expected effects, whereas red points represent trials with unexpected effects. Error bars denote the standard error of paired differences, computed separately for each comparison of expectedness (Pfister & Janczyk, 2013). See the online article for the color version of this figure.

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uncertain whether it is the expectancy violation, or just a superficial mismatch between S1 and E1, irrespective of any expectation, that caused the observed Task 2 slowdown. To disentangle the S1-induced E1-expectancy from the superficial perceptual S1-E1 overlap, we replaced the colored squares of S1 with corresponding letters, thereby eliminating any perceptual S1-E1 similarity.

Method

Forty-eight new participants (34 females, M_{age} = 26.2 years, *SD* = 8.7) were recruited. This ensures a power of >.95 at an alpha of .05 to detect monitoring of effect-errors, assuming an effect size as observed in Experiment 2. Due to the ongoing coronavirus pandemic, data were collected online. Thirty-six participants were replaced due to high (27 participants) or low (nine participants) error rates (see Appendix B). Stimuli and procedure were exactly as in Experiment 1, but letters in white font (S1; "R" = red, "G" = green, "B" = blue) replaced the colored squares in Task 1 (see Appendix D Table D1 for the full instructions).

Results

Data were treated and analyzed as in Experiment 1 and 2 (see Figure 5). After excluding Task 1 omissions (1.5%) and Task 2 errors (10.0%), the sample for RT analyses consisted of 88.9% of the original trials.

Task 1 RTs

Correct R1s (734 ms) were faster than incorrect R1s (777 ms), $F(1, 47) = 9.54$, $p = .003$, $\eta_p^2 = .17$. All other *F*s < 1.21, all *p*s > .279.

Task 1 Error Rates

Participants committed an average of 11.5% (*SD* = 5.3%) Task 1 errors.

Task 2 RTs

Task 2 RTs were lower after a correct R1 (561 ms) than after an incorrect R1 (718 ms), $F(1, 47) = 101.02$, $p < .001$, $\eta_p^2 = .68$. Further, Task 2 responses were faster after an expected E1 (628 ms) than after an unexpected E1 (651 ms), $F(1, 47) = 10.34$, $p = .002$, $\eta_p^2 = .18$. Again, there was no interaction between R1 accuracy and E1 expectancy, $F(1, 47) = 0.14$, $p = .715$, $\eta_p^2 < .01$, BF_{10} = 0.11 (BF_{01} = 8.97).

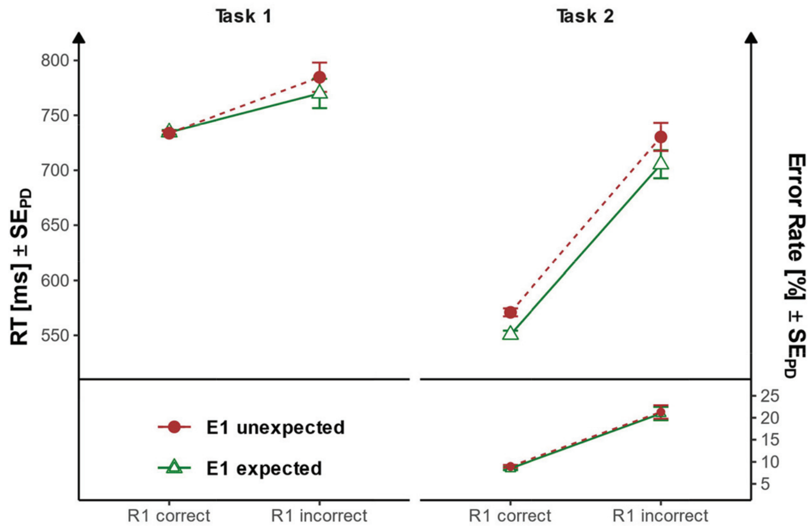
Task 2 Error Rates

Task 2 error rates were higher after an incorrect R1 (21.1%) than after a correct R1 (8.7%), $F(1, 47) = 55.33$, $p < .001$, $\eta_p^2 = .54$. All other *F*s < 1.

Discussion

In Experiment 3, incorrect R1s were slower than correct R1s. While we are not the first to observe this error slowing in a choice RT task (e.g., de Bruijn et al., 2003; Pfister & Foerster, 2021), we can only speculate about its potential origin. It might, for example, reflect increased variability in evidence accumulation due to the switch to online data acquisition (Ratcliff & Rouder, 1998). Likewise, the generally increased response times might have given participants sufficient time for error monitoring based on feed-forward models (Rabbitt, 1978; Ruiz et al., 2009). Future research should aim to investigate this theoretically challenging phenomenon.

Figure 5
Results of Experiment 3



Note. Response times (RTs; top) and error rates (bottom) for Task 1 (left) and Task 2 (right). Green triangles represent trials with expected effects, whereas red points represent trials with unexpected effects. Error bars denote the standard error of paired differences, computed separately for each comparison of expectedness (Pfister & Janczyk, 2013). See the online article for the color version of this figure.

The other results closely replicate the first two experiments. Once again, response-errors and effect-errors of Task 1 were monitored, combined additively, and resulted in Task 2 performance decrements. Therefore, the observed costs of effect monitoring do not reflect a pure perceptual S1-E1 mismatch, which could not occur in this experiment.

Exploratory Analysis

An apparent drawback of the proposed two-component model of monitoring (more precisely: of the observed outcomes) is that it revolves around retaining the null hypothesis of the interaction effect of the Task 2 RTs. To provide enough sensitivity to detect effect sizes of $\eta^2 > .03$ at an alpha of .05 and power of .99, the data from all experiments were pooled (N = 144) and a 2 × 2 × 3 mixed ANOVA with R1 accuracy (correct vs. incorrect) and E1 expectancy (expected vs. unexpected) as within-subjects factors and experiment (Experiment 1 vs. Experiment 2 vs. Experiment 3) as between-subjects factor was conducted for Task 2 RTs, see Appendix C Table C1 for a descriptive comparison of the other variables.

Results

Task 2 RTs differed between Experiment 1 (567 ms), Experiment 2 (529 ms), and Experiment 3 (639 ms), $F(2, 141) = 9.56$, $p < .001$, $\eta_p^2 = .12$. Also, Task 2 responses were faster after a correct R1 (512 ms) than after an incorrect R1 (645 ms), $F(1, 141) = 225.28$, $p < .001$, $\eta_p^2 = .62$. Further, Task 2 RTs were lower after an expected E1 (566 ms) than after an unexpected E1 (591 ms), $F(1, 141) = 34.61$, $p < .001$, $\eta_p^2 = .20$. Fundamentally, there was no interaction between R1 accuracy and E1 expectancy, $F(1, 141) = 0.07$, $p = .796$, $\eta_p^2 < .01$. Bayes Factors revealed strong evidence for the additive combination of these factors, $BF_{10} = 0.06$ ($BF_{01} = 16.02$). All other Fs < 2.85, all ps > .061.

Discussion

We still found no evidence for an interactive influence of response-errors and effect-errors on the duration of the monitoring process. This null effect was corroborated by a Bayesian analysis yielding substantial evidence in favor of additivity.

General Discussion

Summary

In many natural settings, which encompass nondeterministic response-effect relationships, a deviation from an intended end-state can result from the agent selecting an inappropriate motor activity, or from irregularities in the environment. Therefore, humans must monitor both, which actions they chose, and what these actions brought about in the environment. To investigate the monitoring of responses and response effects as well as their relationship, a dual-task setup was used. For Task 1, the action effect was independent of the response, allowing for a separate assessment of the two monitoring components. While this action effect was displayed, participants performed Task 2. Because preceding studies suggest that monitoring cannot run in parallel with another task (Jentzsch & Dudschig, 2009; Wirth, Janczyk, & Kunde, 2018), we expected both unintended motor behavior (response-errors) as well as unintended action effects (effect-errors) to prolong Task 2 response times.

These predictions were consistently confirmed by the data. Task 2 response times were slower after both response-errors and effect-errors. This signifies that we monitor *what* we did as well as

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how we did it. The influences of response-errors and effect-errors on Task 2 performance were additive, indicating independent feedback loops (Logan & Crump, 2010).

Theoretical Implications

The existence of a response monitoring system is so self-evident that it has never been seriously challenged. It was less clear, though, if this monitoring draws on scarce mental resources and thus interferes with processing of concurrent tasks. While one could argue that the observed Task 2 slowing reflects a more conservative response criterion after erroneous responses (Botvinick et al., 2001; Dutilh et al., 2012; Rabbitt & Rodgers, 1977), this should not only result in higher response times, but also decreased error rates. As the error rates increased after response-errors in Task 1, such a shift in the speed-accuracy trade-off can be ruled out for the present experiments. Therefore, our results provide unambiguous evidence that monitoring of both, responses and response effects, is indeed resource-consuming (cf. Welford, 1952).

Our definition of monitoring includes the detection as well as the processing of events. Hence, it is unsurprising that monitoring costs depend on numerous factors (e.g., Houtman & Notebaert, 2013; Kunde et al., 2018; Wirth, Janczyk, & Kunde, 2018; Wirth & Kunde, 2020). Monitoring also incorporates (but is not confined to) an orienting response (Notebaert et al., 2009) to low-probability events. While the present data cannot further differentiate between the share of different cognitive processes, the orienting account contributes one especially important caveat:

It seems tempting to conclude that response-errors impact subsequent tasks more than effect-errors when considering the magnitude of the monitoring costs we observe. However, such a comparison is highly misleading, as both behavioral (Jentzsch & Leuthold, 2006; Notebaert & Verguts, 2011; Steinborn et al., 2012) and neural (Castellar et al., 2010; Gehring et al., 1993; Hajcak et al., 2003) indices of posterror processes depend largely on the error frequency. Hence, decreased error rates presumably lead to increased monitoring costs. In the current experiments, the likelihood of effect-errors (25%; fixed by design) exceeded the rate of response-errors (11%; constrained by the participant exclusion criteria). Therefore, the observation that monitoring of responses elicits larger performance decreases than monitoring of response effects directly follows from the predictions of the orienting account. If, however, effect-errors outnumber response-errors, monitoring of response effects might predominantly affect subsequent tasks (see pilot study, Appendix A, as a tentative hint).

Of most theoretical interest is the independent monitoring of response-errors and effect-errors. We observed statistical independency in a common dependent variable, whereas previous research rested on the selective influence of the two processes on different dependent variables (Logan & Crump, 2010). Additionally, and following our conception of effect expectancy, the anticipation of an action effect was conditional on the intended response (based on the imperative stimulus), not the actual, executed response. Consequently, prolonging response monitoring (by committing a response-error) did not influence effect monitoring (by encountering an effect-error).

Practical Implications

Consider why such a division into separate modules makes sense. Most of our intentions and actions unfold gradually and are temporally extended. They are permanently altered by environmental changes. To successfully operate in such a fluid and nondeterministic setting, higher-level goals must be broken down and chained into a sequence of individual decisions, each adjustable on the fly. The movement of a finger may constitute a subgoal for turning on a light, which in turn might only be a partial prerequisite of yet a higher goal level. It seems reasonable to think of monitoring as equally hierarchical (Wessel, 2018; Yeung & Summerfield, 2012), consisting of several modular and functionally distinct parts that transmit information only sparsely. Instantaneously updating the expectancy of a bright room after missing the light switch would be maladaptive. Rather, this motor error entails the need for a corrective movement of the finger, an adjustment in the same module. Of note, this implies that the observed independency exists on a rather short time scale. It seems self-evident to us that the system, if given sufficient time, integrates information from different sources.

These considerations (as well as our observations) are substantiated by electroencephalographic findings. While error and action-effect monitoring rely on similar generator structures (Holroyd & Coles, 2002), their neural signatures are dissociable (Gentsch et al., 2009; Steinhauser & Kiesel, 2011). Therefore, they have been regarded as instances of a generic monitoring system detecting unexpected events (Band et al., 2009; Wessel et al., 2012). However, the integration of accumulated information seems to take place after this initial assessment of prediction errors (Kalfaoğlu et al., 2018; Steinhauser & Steinhauser, 2021; Steinhauser & Yeung, 2010; Ullsperger et al., 2014), supporting a hierarchical model of monitoring and thus, the observed independency.

Conclusion

The present experiments provide evidence that monitoring involves two distinct feedback loops. One that monitors responses (or feedback from such efferent activities) and one that monitors environmental response effects. Both internally generated response-errors and externally provided effect-errors delayed response times of a subsequent task. Thus, the two monitoring processes are resource-consuming. These influences were additive, suggesting independency.

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Appendix A

Pilot Study

We initially conducted a slightly different version of Experiment 1 but due to sizable error rates in both Task 1 (37.7%) and Task 2 (29.4%), we decided to replicate the results with a modified setup.

Method

Forty-eight participants (39 females, $M_{\text{age}} = 26.8$ years, $SD = 9.4$) were recruited. Apparatus, stimuli, and procedure were exactly as in Experiment 1, but in between blocks, the instructions were not repeated and no feedback on the error rates was given.

Results

Data was treated and analyzed as in Experiments 1, 2, and 3. After excluding Task 1 omissions (3.0%) and Task 2 errors (29.4%), the sample for RT analyses consisted of 68.4% of the original trials.

Task 1 RTs

No influences on Task 1 RTs were observed, all $F\text{s} < 1.05$, all $p\text{s} > .313$.

Task 2 RTs

Task 2 RTs were only descriptively lower after a correct R1 (482 ms) than after an incorrect R1 (510 ms), $F(1, 47) = 3.59$, $p = .064$, $\eta_p^2 = .07$. Further, Task 2 responses were faster after an expected E1 (475 ms) than after an unexpected E1 (516 ms), $F(1, 47) = 12.42$, $p = .001$, $\eta_p^2 = .21$. There was no interaction between R1 accuracy and E1 expectancy, $F(1, 47) = 1.76$, $p = .191$, $\eta_p^2 = .04$.

Task 2 Error Rates

Task 2 error rates were higher after an incorrect R1 (35.6%) than after a correct R1 (28.9%), $F(1, 47) = 21.03$, $p < .001$, $\eta_p^2 = .31$. All other $F\text{s} < 1$.

Discussion

While the pattern of results was as expected, we did not want to draw any conclusions based on a sample with such highly frequent errors. To achieve a more confined range of error rates in Experiment 1, we defined the strict exclusion criteria specified in Appendix B. Furthermore, we displayed adaptive feedback on the error rates and an additional reminder on the instructions in between blocks.

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Appendix B

Replacement of Subjects

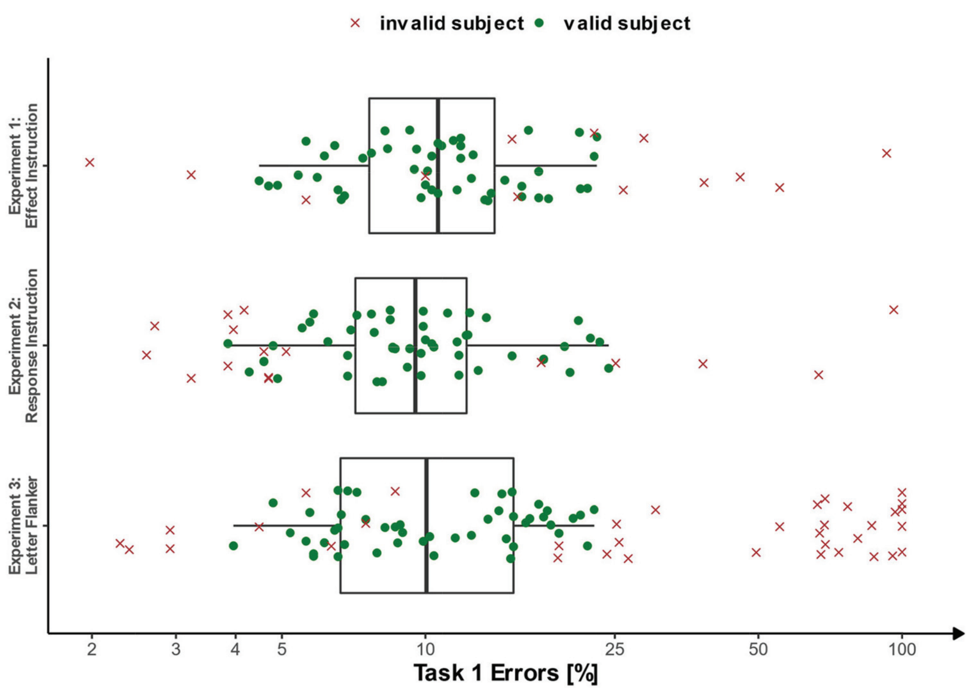
We replaced a substantial fraction of the participants as they did not fit the a priori defined criteria for inclusion in the statistical analysis. To provide stable estimates and control for homoscedasticity, each participant had to contribute more than $2^3 = 8$ valid observations per experimental condition. Further, participants had to achieve an accuracy of at least 75% in both tasks to ensure adequate commitment and comprehension of the instructions.

Four (Experiment 1), 11 (Experiment 2), and nine (Experiment 3) participants were replaced due to insufficient cell allotment of the Mistake condition. We additionally rejected nine (Experiment 1), five (Experiment 2), and 27 (Experiment 3) participants due to their error rates. The steep increase of rejections in the online Experiment 3 was caused by 18 participants performing at or below chance level, compared with one in the offline Experiment 1 and two in Experiment 2 (see Figure B1).

We believe that this meticulous examination of subjects renders the present study especially valuable, as it assures low unsystematic variation in the data. As Sternberg (1969) already noted, "experimental artifacts are more likely to obscure true additivity of factor effects than true interactions" (p. 287).

Figure B1

Exclusion of Participants, Conditional on Their Performance



Note. Subjects had to provide an error rate of less than 25% in both tasks and each experimental cell had to contain more than eight observations. Subjects included in the statistical analysis are marked with a green dot, excluded subjects with a red cross. Boxplots show the distribution of Task 1 error rates for valid subjects. See the online article for the color version of this figure.

(*Appendices continue*)

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Appendix C

Overview Over Reaction Times and Error Rates

Table C1

M ± SD for Reaction Times (RT; in Milliseconds) and Error Rates (PE; in %) for All Experiments and Experimental Conditions

Experiment	Task	Variable	R1 correct, E1 expected	R1 correct, E1 unexpected	R1 incorrect, E1 expected	R1 incorrect, E1 unexpected	Total
Pilot	Task 1	RT	631 ± 144	620 ± 139	632 ± 188	630 ± 174	629 ± 151
		PE	—	—	—	—	37.9 ± 27.4
	Task 2	RT	454 ± 123	510 ± 195	497 ± 161	523 ± 183	467 ± 131
		PE	28.6 ± 27.2	29.3 ± 27.9	35.6 ± 23.9	35.6 ± 23.5	29.7 ± 26.7
Experiment 1	Task 1	RT	654 ± 96	654 ± 94	651 ± 147	672 ± 160	653 ± 98
		PE	—	—	—	—	11.6 ± 5.0
	Task 2	RT	498 ± 84	531 ± 108	606 ± 136	634 ± 161	513 ± 89
		PE	9.1 ± 5.3	10.0 ± 6.4	21.5 ± 12.6	21.4 ± 14.4	10.6 ± 5.9
Experiment 2	Task 1	RT	633 ± 102	630 ± 103	646 ± 162	649 ± 156	634 ± 106
		PE	—	—	—	—	10.6 ± 5.1
	Task 2	RT	453 ± 78	471 ± 88	584 ± 158	608 ± 168	468 ± 82
		PE	8.4 ± 4.5	7.5 ± 3.9	17.2 ± 9.1	17.0 ± 10.3	9.1 ± 4.4
Experiment 3	Task 1	RT	735 ± 125	734 ± 124	770 ± 167	785 ± 186	737 ± 125
		PE	—	—	—	—	11.5 ± 5.3
	Task 2	RT	551 ± 123	571 ± 128	705 ± 179	730 ± 202	566 ± 126
		PE	8.4 ± 4.2	8.9 ± 4.4	20.9 ± 12.8	21.3 ± 15.7	9.7 ± 4.8

Appendix D

Instructions of the Experiments

Table D1

Instructions of the Experiments

Experiment	Instructions
Pilot + Experiment 1	You will work on two alternating tasks. First, turn on a lightbulb in a certain color. Then, respond to a letter as quickly as possible. Underneath the lightbulb you will see some colored squares. Always turn on the lightbulb in the color of the central square. For red, press A. For green, press S. For blue, press D. Try to turn on the lightbulb as quickly as possible. After the lightbulb is switched on, a letter will appear in the center of the screen. In case of an H, press N. In case of an S, press M. Again, try to react as quickly as possible.
Experiment 2	You will work on two alternating tasks. First, respond to the central colored square. Then, respond to a letter as quickly as possible. At the bottom of the screen you will see some colored squares. Always react to the color of the central square. If it is red, press A. If it is green, press S. If it is blue, press D. Try to react as quickly as possible. After your response, a letter will appear in the center of the screen. In case of an H, press N. In case of an S, press M. Again, try to react as quickly as possible.
Experiment 3	You will work on two alternating tasks. First, turn on a lightbulb in a certain color. Then, respond to a letter as quickly as possible. Underneath the lightbulb you will see some letters. Always turn on the lightbulb in the color of the central letter. For R as in red, press A. For G as in green, press S. For B as in blue, press D. Try to turn on the lightbulb as quickly as possible. After the lightbulb is switched on, a letter will appear in the center of the screen. In case of an H, press N. In case of an S, press M. Again, try to react as quickly as possible.

Note. The instructions were in German, with the S-R mapping for both tasks counterbalanced between participants.

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