Published in final edited form as:
J Exp Psychol Gen. 2022 June ; 151(6): 1325–1340. doi:10.1037/xge0001142.

Action errors impair active working memory maintenance

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Abstract

The ability to detect and correct action errors is paramount to safe and efficient behavior. Its underlying processes are subject of intense scientific debate. The recent adaptive orienting theory of error processing (AOT) proposes that errors trigger a cascade of processes that purportedly begins with a broad suppression of active motoric and – crucially – cognitive processes. While the motoric effects of errors are well established, an empirical test of their purported suppressive effects on active cognitive processes is still missing. Here, we provide data from six experiments clearly demonstrating such effects. Participants maintained information in verbal working memory (WM) and performed different response conflict tasks during the delay period. Motor error commission during the delay period consistently reduced accuracy on the WM probe, demonstrating an error-related impairment of WM maintenance. We discuss the broad theoretical and practical implications of this finding, both for the AOT and beyond.

Introduction

Action error processing is a fundamental aspect of human cognition, which combines the human ability to predict action outcomes with their ability to detect and correct deviations from those predictions. The study of performance-monitoring goes back to the seminal work on post-error processing performed by Laming and Rabbitt (Laming, 1979; Rabbitt & Rodgers, 1977) and has since spawned many comprehensive theories about the underlying psychological and neural processes. These theories can be roughly classified with regards to their predictions about the purpose of post-error processing. Adaptive theories – e.g., the mismatch theory (Carter et al., 1998), the conflict-monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001), and the reinforcement-learning theory (Holroyd et al., 2004) – implicitly or explicitly propose that post-error processing is designed to improve subsequent behavior. Contrarily, more recent ‘maladaptive’ theories – e.g., the orienting

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theory (Notebaert et al., 2009) and the bottleneck theory (Jentzsch & Dudschig, 2009) – propose that errors impair subsequent behavior, either because they produce a distracting orienting response, or because their processing takes resources away from the proper processing of subsequent stimuli.

As neither group of theories can account for all seminal findings in the field of error processing, we have recently proposed another recent theoretical account – the adaptive orienting theory (AOT Wessel, 2018). The AOT synthesized predictions from both classes of theories to propose that errors trigger a multi-step processing cascade that is ultimately geared at improving subsequent behavior, but begins with a cascade of processes that can be detrimental to active cognitive and motor processes. This purported cascade begins with the rapid deployment of a non-selective neural mechanism for inhibition (Wessel & Aron, 2017). The proposed function of this inhibitory effort is to facilitate orienting towards the source of the error by disengaging from active mental representations, and furthermore to free up cognitive resources towards implementing adaptive processes that ultimately improve subsequent behavior. Notably, the hypothesized initial inhibition of cognition and motor activity is purportedly broad, in that it non-selectively affects ongoing processes, including processes that are unrelated to the task that led to the error (cf., Wessel & Aron, 2017). While other tenets of the AOT have since been confirmed in recent studies (e.g., Li et al., 2020; Parmentier, Vasilev, & Andrés, 2019), evidence for the purported inhibition of active cognitive processes due to action errors is still missing. While there is some evidence to suggest that errors affect non-motor processes (Buzzell, Beatty, Paquette, Roberts, & McDonald, 2017; Houtman & Notebaert, 2013; Purcell & Kiani, 2016), these studies describe impairments of perceptual processes in the aftermath of error commission. No demonstration of impaired cognitive processes that are active at the time of error commission hitherto exists.

In the current study, we demonstrate this phenomenon across seven experiments. In the first six experiments, subjects maintained a string of letters in WM across a delay period, whereas in the seventh experiment, they maintained the colors of an array of squares. During the delay period, they performed several trials of a conflict task (either an arrow Flanker task, (Eriksen & Eriksen, 1974); a temporal Flanker task, (Schumacher, Schwarb, Lightman, & Hazeltine, 2011); a spatial Stroop task, (Lu & Proctor, 1995); or a color Simon task, (Simon & Rudell, 1967)). The dependent variable of interest was accuracy on the subsequent WM probe, depending on whether or not an error was made during the delay period. The WM accuracy was measured using both memory recognition (Experiment 1–6) and memory recall (Experiment 7) tasks. We hypothesized that conflict-task errors would impair active WM maintenance and, consequently, impair subsequent retrieval of the WM contents, reducing WM accuracy after errors.

Experiment 1

Method

Participants.—A target sample size of 53 was determined based on alpha-level of .05, power-level of 0.80 and an estimated effect size of 0.39 from a pilot study. The same target sample size was applied to the first five experiments. Sixty-one participants gave informed consent, in accordance with procedures approved by the University of Iowa Institutional Review Board (UIIRB #202001345) and completed this experiment via Amazon Mechanical Turk (MTurk). Participants performed tasks in their web browser. Although online experimentation prevented us from monitoring the environment in which the participants performed the task, participant performance was well above chance in both aspects of the task (WM and conflict processing). Furthermore, we included manipulation checks in the paradigm, specifically replicating classic findings in the literature (e,g., conflict interference effects) before testing the main hypotheses. Therefore, it was ensured that participants followed the instructions and were attentive to the tasks. In all experiments, participants were compensated based on an hourly rate of $8.00. Eight subjects were excluded due to having below threshold number of WM trials in any post-error experimental conditions or excessive number of trials with no response to WM probe (see Data analysis for threshold calculation). The final sample size was 53 (17 females, 36 males; age: M = 35.10 years, SD = 8.17, 1 not reported).

Stimuli.—Stimuli included English consonants in upper case and arrow characters “<” and “>”. Unless noted otherwise, all stimuli were presented in black color on a grey background in the center of a web browser window, which the participants used to perform the experiment. The tasks were programmed using JavaScript and JQuery 3.5.0. The protocols for online data acquisition was adopted from previous MTurk studies on WM (Kiyonaga & Egner, 2014) and interference effects in conflict tasks (Bejjani, Zhang, & Egner, 2018; Weissman, Jiang, & Egner, 2014).

Procedure.—The structure of a WM trial was shown in Fig. 1. Each WM trial started with the presentation of a fixation cross for 1,000 ms, followed by a string of unique consonants presented for 2,000 ms. Participants were instructed to remember this string for a later test. The string was followed by a delay period of 7,200 ms, during which the participants performed six conflict task trials. In this experiment, the conflict task was a Flanker task. On each Flanker trial, distractors (two flanker arrows pointing to the same direction) and a blank placeholder for the forthcoming target were presented for 50 ms. The target (a center arrow) was then presented along with the distractors for 950 ms. Depending on the match or mismatch between the target and the distractions, a Flanker trial can be either congruent or incongruent, respectively. Participants were instructed to ignore the distractors and respond to the direction of the center arrow by pressing the left or right arrow key. Flanker trials were separated by a fixed inter-trial interval (ITI) of 200 ms, during which a blank screen was presented. The delay period was followed by a WM probe string, which either matched the original string (50% probability) or differed from it by one letter (50% probability; except for the first letter, which always matched the original string – though this was unbeknownst to the participants). The probe was presented for 2,000 ms. Participants were instructed to press up/down arrow key to indicate their judgement of match/mismatch, respectively. This procedure is a modified version of the classic Sternberg task (Sternberg, 1966), adapted from a previous study on the effects of unexpected events on WM maintenance (Wessel et al., 2016). In all experiments, participants were instructed to emphasize accurate responding to the WM probe.

The experiment consisted of three parts, after which participants could take self-timed breaks. The first part was a practice consisting of five WM trials with a constant WM load (i.e., string length) of 4 for the participants to learn the trial structure and response mappings. The distractors in conflict trials during delay period were removed to facilitate learning of response mapping. Feedback (“correct”, “incorrect”, or “no response”) was presented on the screen following each conflict task trial and the WM probe. The second part was a calibration procedure (ten blocks of ten WM trials each without feedback), which adapted the WM load to individual performance. Participants were not informed of the purpose of this part of the task. The WM load in this calibration was initially set to 4. Following each block, if the block-mean response accuracy to the WM probe was higher than 0.8 or lower than 0.7, the WM load increased/decreased by one, respectively. Otherwise, the WM load remained unchanged. Participants were excluded from completing the experiment if their WM load fell below 3. Similar to the practice, distractors in conflict task trials were removed. The third part was the main task, which consisted of five blocks of 30 WM trials each without feedback. The WM load in main task was set to the WM load at the end of the calibration and remained constant from there onwards. Within each block, six WM trials had all congruent Flanker trials and are termed Pure trials (no conflict). The other 24 WM trials had three congruent and three incongruent Flanker trials (distributed randomly) and were termed Mixed trials. Based on whether an error was made on the Flanker trials during the delay period, WM trials were further categorized into Pure-correct, Pure-error (not analyzed due to low trial counts), Mixed-correct and Mixed-error conditions.

Data analysis.—Behavioral data from the main task were analyzed. To prevent the processing of missed responses from confounding post-error processing, conflict task trials on which no response was made (and the corresponding WM trials that contained them) were excluded from further analyses. WM trials with no response to WM probe were also excluded. Including these trials as errors trials did not qualitatively change the results. For Mixed-correct and Mixed-error WM trials, the threshold for subject exclusion was set to the larger of 10 and 3*SD*s below group median. Subjects with excluded WM trials more than 3*SD*s above group median were also excluded.

All statistical tests were two-tailed unless noted otherwise. To validate the manipulation of conflict, we compared accuracy and mean response time (RT) between congruent and incongruent conflict trials using paired t-tests. As a measure of post-error processing, we tested the difference in accuracy and mean RT between post-correct and post-error trials, collapsing across congruency conditions on current trial. We further compared the interference effects (incongruent condition – congruent condition), calculated separately using accuracy and RT, between trials following correct incongruent and error incongruent trials using paired t-tests. The post-error analyses were constrained to previously incongruent trials due to low number of error congruent trials. Subjects with less than five trials in any of the conditions of the previous (correct vs. error) × current trial (congruent vs. incongruent) design were excluded from these analyses.

As planned analyses of interest, we tested the error-related impairment of active working memory (ERIAM) – i.e., the purported reduction in WM performance following errors on the conflict task – by comparing the accuracy and mean RT to WM probe in the

Mixed-correct to their counterparts in the Mixed-error condition using paired t-tests. Note the conflict level was controlled by keeping it constant (i.e., 50% congruent trials and 50% incongruent trials) across the two conditions. We also independently tested the effect of conflict during the delay period on WM performance by comparing the accuracy and mean RT to WM probe in the Pure-correct to their counterparts in the Mixed-correct condition using paired t-tests. Note that no errors occurred in conflict trials in these two conditions, thus the conflict effect on WM performance was not confounded by errors and post-error processing.

After Experiment 1 concluded, we further hypothesized that subjects who show lower overall WM accuracy (indicative of a less stable WM representation) will show stronger ERIAM effects, as their WM representations may be more readily subject to impairment. Hence, we predicted a negative correlation between overall WM performance and the ERIAM effect. As an exploratory analysis to test this post-hoc hypothesis, we operationalized the overall WM performance as the average of WM accuracy across Mixed-correct and Mixed-error conditions, and measured its correlation with WM accuracy difference between these two conditions (i.e., ERIAM) across subjects using Pearson's r. To address the potential confound that this correlation may be affected by the covariance structure between Mixed-correct and Mixed-error conditions, we conducted a non-parametric statistical test: We simulated subject-level WM accuracy for Mixed-correct and Mixed-error conditions using two groups of randomly generated numbers, with the constrains that (1) the group size was set to the number of subjects in this experiment; (2) the means and covariance structure of empirical data were used in the simulation; and (3) the correlation coefficient of between the two groups of simulated data differed from the cross-subject correlation coefficient between Mixed-correct and Mix-error accuracy by less than 0.01. To simulate the predicted correlation, Pearson's r was calculated between the mean across the two groups (simulating overall WM performance) and their difference (simulating ERIAM). This procedure was repeated for 10,000 times to estimate a null distribution of correlation coefficient between overall WM accuracy and ERIAM, while controlling for mean difference and covariance structure of WM accuracy between Mixed-correct and Mixed-error conditions. P-values derived from the null distribution were one-tailed, as the null distribution was not necessarily centered at 0 or symmetric.

Results

Conflict task results.—Results are illustrated in Fig. 2. Summary statistics are listed in Table 1. Compared to congruent trials, incongruent trials displayed lower accuracy (t_{52} = 9.57, $P < 0.001$, Cohen's d = 1.31) and slower RT (t_{52} = 22.66, $P < 0.001$, Cohen's d = 3.11), indicating standard conflict interference effects on both DVs, hence validating the experimental manipulation of conflict. We found no significant difference in accuracy (t_{35} = 1.03, $P > 0.31$, Cohen's d = 0.17) between post-error and post-correct trials. Post-error trials were marginally faster than post-correct trials (t_{35} = 1.98, $P = 0.055$, Cohen's d = 0.33). Post-error changes in conflict interference were observable for neither accuracy (t_{35} = 1.09, $P > 0.28$, Cohen's d = 0.18) nor RT (t_{35} = 1.04, $P > 0.30$, Cohen's d = 0.17).

WM results.—Results are visualized in Fig. 3. Summary statistics are listed in Table 1. The WM load of participants ranged from 3 to 10 letters (M = 6.75, SD = 1.61). As a test of whether conflict during delay period influences WM performance, WM accuracy and RT in Mixed-correct condition were compared to their counterparts in Pure-correct condition. Neither result reached statistical significance (Accuracy: $t_{52} = 0.82$, $P > 0.41$, Cohen's $d = 0.11$; RT: $t_{52} = 1.09$, $P > 0.28$, Cohen's $d = 0.15$), indicating that the presence of conflict in the absence of errors did not change WM performance.

The key research question of this study was the effect of action error commission in the delay period on WM accuracy to the subsequent probe. To this end, we conducted two analyses: First, the test of ERIAM revealed significantly higher WM accuracy for Mixed-correct than Mixed-error condition ($t_{52} = 2.32$, $P = 0.025$, Cohen's $d = 0.32$), with small-to-medium effect size. RTs did not differ significantly between the two conditions ($t_{52} = 0.41$, $P > 0.68$, Cohen's $d = 0.06$), suggesting that the post-error WM accuracy finding was not due to a speed-accuracy tradeoff. Second, supporting the exploratory prediction that lower overall WM performance is linked to larger ERIAM effects, we found a significant negative correlation between overall WM accuracy across the Mixed-correct and Mixed-error conditions and the ERIAM effect ($r = -0.46$, $P < 0.034$; Figure 3, top row, right column).

Experiment 2

Experiment 1 demonstrated the ERIAM effect. An exploratory analysis also showed a correlation between overall WM accuracy ERIAM across subjects, indicating that ERIAM was stronger in subjects with less stable WM loads. Additionally, our comparison between mixed correct and pure correct trials showed that ERIAM could not be explained by conflict alone.

In Experiment 2, we attempted to replicate ERIAM using different timing parameters, specifically, with a longer inter-trial interval for the conflict task. This was motivated by the fact that the bottleneck theory of error processing (Jentzsch & Dudschig, 2009) proposes that with more available processing time after the response, the adverse effects of post-error processing (including, perhaps, ERIAM) may wear off. Furthermore, we aimed to replicate the exploratory correlation analysis between overall WM accuracy and ERIAM, this time as an a priori hypothesis.

Method

Participants.—Seventy participants gave informed consent, in accordance with procedures approved by UIIRB #202001345 and completed this experiment via MTurk. Seventeen subjects were excluded (same exclusion criteria as in Experiment 1). The final sample size was 53 (20 females, 33 males; age: *M* = 39.13 years, *SD* = 9.11).

Stimuli.—Stimuli were identical to Experiment 1.

Procedure.—The procedure was identical to Experiment 1, except for the changes to the presentation duration of the target stimulus and the ITI (100 ms and 2300 ms), respectively.

Target stimulus duration was decreased relative to Experiment 1 to increase the difficulty of the conflict task to countermand the longer ITI. Additionally, to make the duration of the delay period comparable to Experiment 1, the number of Flanker trials was reduced to 4, while maintaining the 50% proportion of incongruent trials. The Pure condition was also removed, in order to keep the total length of the experiment similar to Experiment 1 (and since Experiment 1 indicated no effects of conflict on WM performance – i.e., no difference between the Pure-correct and Mixed-correct trials). This change resulted in 5 blocks of 24 WM trials each.

Data analysis.—Data analysis was identical to Experiment 1, except that no Pure-correct trial condition was present.

Results

Conflict task results.—Behavioral results are visualized in Fig. 2. Summary statistics are listed in Table 1. Compared to congruent trials, incongruent trials resulted in lower accuracy ($t_{52} = 9.57$, $P < 0.001$, Cohen's d = 1.31) and slower RT ($t_{52} = 20.26$, $P < 0.001$, Cohen's d = 2.78), replicating the conflict interference effect and thus validating the experimental manipulation of conflict. Trials following error trials were less accurate ($t_{40} = 2.07$, $P = 0.045$, Cohen's d = 0.32) and marginally faster ($t_{40} = 1.80$, $P = 0.079$, Cohen's d = 0.28) than those following correct trials. Post-error increases in conflict interference were found in both accuracy ($t_{40} = 2.03$, $P = 0.049$, Cohen's d = 0.32) and RT ($t_{40} = 2.42$, $P = 0.02$, Cohen's d = 0.38).

WM results.—Results are visualized in Fig. 3. Summary statistics are listed in Table 1. The WM load ranged from 3 to 11 letters ($M = 6.34$, $SD = 1.65$). We replicated the ERIAM effect on WM accuracy ($t_{52} = 3.29$, $P = 0.002$, Cohen's d = 0.45), with medium effect size, and again found no effect of conflict-task errors on WM task RT ($t_{52} = 0.68$, $P > 0.49$, Cohen's d = 0.09). We also observed a marginally significant negative correlation between overall WM accuracy and ERIAM ($r = -0.42$, $P = 0.052$; Figure 3, second row, right column).

Experiment 3

Experiment 2 replicated both ERIAM and the negative correlation between WM accuracy and ERIAM, showing that even when the RSI is ostensibly long enough to overcome a purported post-error bottleneck (Jentzsch & Dudschig, 2009), ERIAM remains in place – and indeed, even increased in effect sized.

In Experiment 3, we attempted to replicate the ERIAM effect using a different conflict task to test its generalizability to other motor tasks.

Method

Participants.—Seventy-three participants gave informed consent, in accordance with procedures approved by UIIRB #202001345 and completed this experiment via MTurk. Twenty subjects were excluded (same exclusion criteria as Experiment 1). The final sample size was 53 (28 females, 25 males; age: $M = 38.50$ years, $SD = 10.63$, two not reported).

Stimuli.—Stimuli included English consonants presented in upper case and black color and asterisks (“*”) presented in either green (color value #307177) or orange (color value #C4854E) color.

Procedure.—The procedure was identical to Experiment 1 with an exception that the Flanker task was replaced with a Simon task. Specifically, on each trial, an asterisk was presented in either green or orange color and on either the left or right side of the web browser window for 1000 ms. Participants were instructed to ignore the location of the asterisk and to respond to its color by pressing left arrow key for orange and right arrow key for green.

Data analysis.—Data analysis was identical to Experiment 1.

Results

Conflict task results.—Behavioral results are visualized in Fig. 2. Summary statistics are listed in Table 1. Compared to congruent trials, incongruent trials yielded lower accuracy ($t_{52} = 9.57$, $P < 0.001$, Cohen’s d = 1.31) and slower RT ($t_{52} = 22.66$, $P < 0.001$, Cohen’s d = 3.11), reflecting conflict interference effects and thus validating the experimental manipulation of conflict. Trials following error trials were less accurate ($t_{46} = 4.14$, $P < 0.001$, Cohen’s d = 0.60) and slower ($t_{46} = 2.16$, $P = 0.036$, Cohen’s d = 0.31) than those following correct trials. Post-error increases in conflict interference were found in both accuracy ($t_{46} = 3.46$, $P = 0.001$, Cohen’s d = 0.50) and RT ($t_{46} = 3.88$, $P < 0.001$, Cohen’s d = 0.56).

WM results.—Results are visualized in Fig. 3. Summary statistics are listed in Table 1. Individual WM load ranged from 3 to 10 letters (M = 5.92, SD = 1.77). We found no statistically significant difference in WM accuracy ($t_{52} = 0.55$, $P > 0.58$, Cohen’s d = 0.08) or RT ($t_{52} = 1.19$, $P > 0.23$, Cohen’s d = 0.16) between Mixed-correct and Pure-correct conditions, indicating that – as in Experiment 1 – WM was unaffected by conflict.

Unlike in Experiments 1 and 2, we found no statistically significant ERIAM effect on the group level ($t_{52} = 0.58$, $P > 0.56$, Cohen’s d = 0.08). In line with Experiments 1 and 2, there was also no effect of conflict-task errors on WM RT ($t_{52} = 0.86$, $P > 0.40$, Cohen’s d = 0.12). We also did not observe a statistically significant correlation between overall WM accuracy and ERIAM ($r = -0.26$, $P > 0.17$; Figure 3, third row, right column).

Experiment 4

Experiment 3 did not show an ERIAM effect on the group level. We hypothesized that the absence of ERIAM in the Simon task may be due to the arbitrary stimulus-response mapping in the conflict task, which introduced an additional, task-related WM requirement (maintaining the S-R mapping). Hence, in Experiment 4, we replaced the arbitrary response mapping with a more intuitive one.

Method

Participants.—Sixty-four participants gave informed consent, in accordance with procedures approved by UIIRB #202001345 and completed this experiment via MTurk. Eleven subjects were excluded (same exclusion criteria as Experiment 1). The final sample size was 53 (34 females, 19 males; age: *M* = 38.21 years, *SD* = 12.47, 1 not reported).

Stimuli.—Stimuli included English consonants and characters "<" and ">".

Procedure.—The procedure was identical to Experiment 2, except the conflict task was replaced with a spatial Stroop task. On each spatial Stroop trial, an arrow character ("<" or ">") was presented on either the left or right side of the web browser window for 100 ms. Participants were instructed to respond to the stimulus by pressing left arrow key for "<" and right arrow key for ">". If no response was detected after 1200 ms following the onset of the target, a warning "Respond faster" was shown at the center of the window.

Data analysis.—Data analysis was identical to Experiment 2.

Results

Conflict task results.—Behavioral results are visualized in Fig. 2. Summary statistics are listed in Table 1. Compared to congruent trials, incongruent trials displayed lower accuracy (t_{52} = 11.83, P < 0.001, Cohen's d = 1.62) and slower RT (t_{52} = 19.54, P < 0.001, Cohen's d = 2.68), reflecting conflict interference effects and thus validating the experimental manipulation of conflict. Trials following errors did not differ from those following correct trials in accuracy (t_{29} = 0.80, P > 0.43, Cohen's d = 0.15) or RT (t_{29} = 2.16, P > 0.78, Cohen's d = 0.05). Post-error increases in interference were found in both accuracy (t_{29} = 2.14, P = 0.041, Cohen's d = 0.39) and RT (t_{29} = 3.57, P = 0.001, Cohen's d = 0.65).

WM results.—Results are visualized in Fig. 3. Summary statistics are listed in Table 1. Individual WM load ranged from 4 to 9 letters (M = 6.30, SD = 1.25). We found no statistically significant ERIAM on the whole group level (t_{52} = 0.86, P > 0.39, Cohen's d = 0.12), though this time we found an increase in RT on the WM probe on trials containing conflict-task errors (t_{52} = 2.14, P = 0.037, Cohen's d = 0.29). Again, however, we replicated the significant negative correlation between overall WM accuracy and ERIAM on WM accuracy (r = −0.51, P = 0.033; Figure 3, fourth row, right column).

Experiment 5

Experiment 4 again showed the hypothesized negative correlation between overall WM accuracy and ERIAM. However, that Experiment found no significant ERIAM for the whole group. This also shows that the absence of ERIAM in Experiment 3 was not due to the additional load that may have been required to encode the stimulus mapping in the Simon task, as Experiment 4 used an intuitive mapping using arrows. However, the consistent WM accuracy – ERIAM correlation across experiments 1, 2, and 4 (which showed the same directionality in Experiment 3 as well) indicates that ERIAM may be dependent on the stability of the WM representation (cf., Experiment 6).

In Experiment 5, we again attempted to replicate ERIAM and the ERIAM-WM accuracy correlation, but with a third conflict task.

Method

Participants.—Sixty-four participants gave informed consent, in accordance with procedures approved by UIIRB #202001345 and completed this experiment via MTurk. Eleven subjects were excluded (same exclusion criteria as in Experiment 1). The final sample size was 53 (17 females, 36 males; age: $M = 35.13$ years, $SD = 8.17$, 1 not reported).

Stimuli.—Stimuli included English consonants and vowels E and U in upper case.

Procedure.—The procedure was identical to Experiment 4, except for two changes. First, the conflict task was replaced with a temporal Flanker task: Each temporal Flanker trial started with the presentation of a distractor consisting of 3 identical vowels (either “UUU” or “EEE”) for 100 ms, followed by presentation of a target (either “U” or “E”) for 150 ms. The target was followed by an ITI of 2250 ms. Participants were instructed to ignore the distractor and respond to the target by pressing left arrow key for “U” and right arrow key for “E”. Second, after the calibration, the participants underwent a practice of five WM trials with feedback to practice the temporal Flanker with distractors.

Data analysis.—Data analysis was identical to Experiment 4.

Results

Conflict task results.—Behavioral results are visualized in Fig. 2. Summary statistics are listed in Table 1. Compared to congruent trials, incongruent trials displayed lower accuracy ($t_{52} = 4.64$, $P < 0.001$, Cohen’s $d = 0.64$) and slower RT ($t_{52} = 13.31$, $P < 0.001$, Cohen’s $d = 1.83$), reflecting conflict interference effects and thus validating the experimental manipulation of conflict. Trials following errors did not differ from those following correct trials in accuracy ($t_{22} = 0.35$, $P > 0.73$, Cohen’s $d = 0.07$) or RT ($t_{22} = 0.39$, $P > 0.70$, Cohen’s $d = 0.08$). No changes in post-error conflict interference were found in accuracy ($t_{22} = 0.66$, $P > 0.50$, Cohen’s $d = 0.14$) or RT ($t_{22} = 0.09$, $P > 0.93$, Cohen’s $d = 0.02$).

WM results.—Results are visualized in Fig. 3. Summary statistics are listed in Table 1. Individual WM load ranged from 3 to 9 letters ($M = 6.17$, $SD = 1.33$). We found no statistically significant ERIAM on the group level ($t_{52} = 1.11$, $P > 0.27$, Cohen’s $d = 0.15$) and no effects of conflict task errors on WM task RT ($t_{52} = 0.86$, $P > 0.39$, Cohen’s $d = 0.12$). However, we again replicated significant negative correlation between overall WM accuracy and ERIAM in accuracy ($r = -0.47$, $P = 0.035$; Figure 3, fifth row, right column).

Experiment 6

In Experiment 5, we again replicated the findings of ERIAM-WM accuracy correlation using a third type of conflict task. Although significant group-level ERIAM was not observed, the consistently observed ERIAM-WM accuracy correlation even in Experiments without significant group-level ERIAM (Experiments 4, 5) led us to hypothesize that ERIAM depends on the stability of the WM representation / the difficulty of the WM component. To test this, we re-ran Experiment 5, but with a more challenging WM load. We hypothesized that we would find a group-level ERIAM effect, even using this paradigm, if the load was sufficiently challenging (and hence, perhaps less stable and more susceptible to ERIAM).

Method

Participants.—The target sample size was increased to 60, in order to raise the statistical power to .85 based on alpha-level of .05 and the estimated effect size of 0.39 from the pilot study. Seventy participants gave informed consent, in accordance with procedures approved by UIIRB #202001345 and completed this experiment via MTurk. Ten subjects were excluded (same exclusion criteria as in Experiment 1). The final sample size was 60 (25 females, 35 males; age: $M = 33.71$ years, $SD = 9.03$, 1 not reported).

Stimuli.—Stimuli were identical to Experiment 5.

Procedure.—The procedure was identical to Experiment 5, except for two changes. First, to increase the difficulty of WM maintenance, the WM load increased by one following the calibration (which was otherwise identical). Second, the duration of WM probe presentation was increased to 2800 ms to accommodate the more challenging WM test. To keep the duration of the WM trial identical to Experiment 5, conflict task ITI was reduced to 2050 ms.

Data analysis.—Data analysis was identical to Experiment 5.

Results

Conflict task results.—Behavioral results are visualized in Fig. 2. Summary statistics are listed in Table 1. Compared to congruent trials, incongruent trials displayed lower accuracy ($t_{59} = 5.16$, $P < 0.001$, Cohen’s $d = 0.67$) and slower RT ($t_{59} = 21.32$, $P < 0.001$, Cohen’s $d = 2.75$), reflecting conflict interference effects and thus validating the experimental manipulation of conflict. Trials following errors were less accurate than those following correct trials ($t_{33} = 2.56$, $P = 0.015$, Cohen’s $d = 0.44$). However, RTs did not differ between post-correct and post-error trials ($t_{33} = 1.66$, $P > 0.10$, Cohen’s $d = 0.28$). No changes in post-error conflict interference were found in accuracy ($t_{33} = 1.24$, $P > 0.22$, Cohen’s $d = 0.21$), whereas post-error conflict interference in RT was larger than post-correct conflict interference ($t_{33} = 3.52$, $P = 0.001$, Cohen’s $d = 0.60$).

WM results.—Results are visualized in Fig. 3. Summary statistics are listed in Table 1. Individual WM load ranged from 4 to 12 letters ($M = 7.50$, $SD = 1.49$). Supporting the primary hypothesis, we found statistically significant ERIAM on the group level (t_{59} = 2.08, P = 0.042, Cohen's d = 0.27). No statistically significant effect of conflict task errors on WM task RT was observed (t_{59} = 1.37, P > 0.17, Cohen's d = 0.18), suggesting that the ERIAM was unlikely to be a result of speed-accuracy tradeoff. The negative correlation between overall WM accuracy and ERIAM in accuracy was marginally significant (r = −0.37, P = 0.071; Figure 3, sixth row, right column).

Experiment 7

To test whether the ERIAM effect generalized to a different type of WM stimulus material, we conducted a final experiment in which we used colors instead of verbal stimuli. Furthermore, instead of a match/mismatch recognition judgment, WM contents were probed in parametric fashion, using cued recall.

Method

Participants.—Sixty-nine participants gave informed consent, in accordance with procedures approved by UIIRB #202001345 and completed this experiment via MTurk. Fifteen subjects were excluded (same exclusion criteria as in Experiment 2, except that participants were excluded if there were fewer than five trials in any WM trial condition). The final sample size was 54 (28 females, 26 males; age: M = 32.72 years, SD = 8.01).

Stimuli.—Stimuli included arrow characters "<" and ">" and 360 colors evenly sampled from the CIELAB color space (parameters: L = 74, A = 0, B = 0, radius = 40 and illuminant = D65).

Procedure.—The structure of a WM trial was shown in Fig. 5. Each WM trial started with the presentation of a fixation cross and a direction cue (letter "L" or "R") above the fixation cross for 500 ms. Then, three colored squares were presented on each of the left and right side of the browser window for 2,000 ms. Colors were randomly chosen from the 360 colors, with the constrain that the no two colors were closer than 20 degrees between each other in the color space. Participants were instructed to remember the colors of the three squares on the side indicated by the direction cue. The color squares were followed by a delay period of 12,000 ms, during which the participants responded to six stimuli of a conflict task. In this experiment, the conflict task was a Flanker task identical to Experiment 1 and 2, except for different timing parameters: The durations for distractors, target and ITI were 200 ms, 800 ms and 1,000 ms, respectively. Additionally, participants were required to use their left middle and index finger to response to left and right arrows, respectively, freeing up their right hand to use the mouse or trackpad to indicate their response on the color wheel. The delay period was followed by a WM probe, in which a color wheel was presented around the center of the browser window along with a black box. Participants were instructed to report the color indicated by the black box by clicking on the corresponding color on the color wheel using their right hand. The color wheel rotated randomly on each trial to discourage the participants to code colors using locations on color wheel (e.g., instead of memorizing the colors green, blue and red, they may memorize 12-, 2-, and 6-clock on the color wheel). When the participants move their mouse on the color wheel, the color being pointed at by the cursor will be shown at the center of the browser window. The probe will end after a maximum of 4,000 ms. The WM aspect of this task is similar to work from Vogel & Machizawa (2004).

The experiment consisted of two parts. The first was a practice of ten WM trials for the participants to learn the trial structure and response mappings. As in experiments 1–6, the distractors in conflict trials during delay period were removed during practice to facilitate learning of response mapping. Feedback (“correct”, “incorrect”, or “no response”) was presented on the screen following each conflict task trial and the WM probe. A WM response was considered correct if the response was within 60 degrees of the actual color. The second part was the main task, which consisted of fifteen blocks of ten WM trials each without feedback. All WM trials had three congruent and three incongruent Flanker trials (distributed randomly) and hence were Mixed trials. No feedback was given to the participants during the main task.

Data analysis.—Data analysis was identical to Experiment 2, except that dependent variable of accuracy in WM performance was replaced with error in degrees at the recall probe. Additionally, due to the lower number of trials in the Mixed-error condition in this paradigm, median WM error and RT were computed for each participant and used in group-level statistical tests.

Results

Conflict task results.—Behavioral results are visualized in middle row of Fig. 5. Summary statistics are listed in Table 3. Compared to congruent trials, incongruent trials resulted in lower accuracy ($t_{53} = 9.23$, $P < 0.001$, Cohen’s $d = 1.26$) and slower RT ($t_{53} = 26.06$, $P < 0.001$, Cohen’s $d = 3.55$), replicating the conflict interference effect and thus validating the experimental manipulation of conflict.

Trials following error trials were less accurate ($t_{46} = 3.16$, $P = 0.003$, Cohen’s $d = 0.46$) and slower ($t_{46} = 5.64$, $P < 0.001$, Cohen’s $d = 0.82$) than those following correct trials. Post-error increases in conflict interference were found in RT ($t_{46} = 3.34$, $P = 0.002$, Cohen’s $d = 0.49$) but not in accuracy ($t_{46} = 0.90$, $P > 0.37$, Cohen’s $d = 0.13$).

WM results.—Results are visualized in bottom row of Fig. 5. Summary statistics are listed in Table 3. Importantly, we replicated the ERIAM effect on WM accuracy ($t_{53} = 2.50$, $P = 0.016$, $d = 0.34$), with medium effect size, and again found no effect of conflict-task errors on WM task RT ($t_{53} = 0.15$, $P > 0.87$, $d = 0.02$). Consistent with Experiments 1, 2, 4, 5, and 6 (as well as the numerical direction in Experiment 3), we again also observed a significant negative correlation between overall WM error and ERIAM on error ($r = -0.52$, $P = 0.018$; Figure 5, bottom row, right column), such that participants showing higher overall WM error exhibited higher ERIAM.

Control analyses

We conducted several control analyses to rule out confounding factors from our results.

First, to rule out that the correlation between ERIAM and WM accuracy was due to inter-subject differences in the exact load that was identified in the calibration phase (regardless of how difficult that specific load was for each subject, which we operationalized as ‘overall WM accuracy’ in our main analysis correlations above), we also correlated the ERIAM effect with each subjects’ net load, regardless of their accuracy for their individual load. This yielded no significant correlations in any of the first six experiments, even before any adjustments for multiple comparisons ($P > 0.29$; $P > 0.19$, $P > 0.94$; $P > 0.70$; $P > 0.14$; $P > 0.83$, respectively; note that load was constant in Experiment 7, so this analysis is impossible). The Bayes factors (alternative over null hypothesis) were 0.19, 0.30, 0.11, 0.12, 0.31 and 0.10, respectively, indicating anecdotal to moderate evidence favoring the null hypothesis of no correlation (Lee & Wagenmakers, 2014). This shows that the susceptibility to ERIAM is not related to a specific participant’s ability to maintain higher WM loads overall, but rather to the difficulty a specific chosen load presented to each individual participant.

Second, to rule out an alternative explanation that participants traded off conflict processing for working memory accuracy, we tested whether the basic conflict interference effect was larger (in either RT or accuracy) depending on whether the WM response was accurate (WM-correct) or incorrect (WM-error). If WM-error trials showed reduced interference, this could suggest that subjects are trading of conflict task performance for WM task performance. We used paired t-tests for these comparisons (see Table 1 for summary statistics). Data from Experiment 7 was not included because WM performance was not a binary variable in that experiment. The analysis yielded no significant results for the RT interference effect in Experiments 1, 4, 5, and 6 (uncorrected p-values: $P > 0.60$; $P > 0.14$; $P > 0.17$; $P > 0.39$, respectively) nor the accuracy interference effect (uncorrected p-values: $P > 0.87$; $P > 0.31$; $P > 0.84$; $P > 0.93$, respectively). In Experiment 2 and 3, we found significant differences in the accuracy interference effect (Experinemtn2: $t_{52} = 2.48$, $P = 0.017$; Experiment 3: $t_{52} = 2.24$, $P = 0.029$), whereas the RT interference effect did not significantly differ between WM-correct and WM-error conditions in either experiment (Experinemtn2: $t_{52} = 1.20$, $P > 0.23$; Experiment 3: $t_{52} = 1.34$, $P > 0.18$). However, the direction of the differences was opposite to the prediction of the alternative explanation: In both Experiment 2 and 3, WM-error trials showed stronger interference effects than WM-correct trials. While this pattern was not reliable across experiments, if anything, the outcome speaks against the alternative explanation.

Third, to investigate whether error position within the delay interval affected the ERIAM effect, we split each participants’ error trials depending on whether the error was made within the first or second half of the delay interval. Data from Experiment 1–6 was combined to ensure statistical power. Data from Experiment 7 was not used due to the different dependent variable used. In participants with a sufficient number of error trials for this analysis (10 trial minimum in both conditions), no difference in ERIAM was found ($t_{132} = 0.27$, $P > 0.78$, $d = 0.02$). The same was true when the sample was limited to participants from Experiments 1, 2, and 6 only (i.e., the experiments that produced significant group-level ERIAM: $t_{73} = 0.17$, $P > 0.87$, $d = 0.02$).

Fourth, the inter-subject correlations between ERIAM and overall WM accuracy were affected by some degree of heteroscedasticity (i.e., with higher overall accuracy, the possible range for ERIAM was larger). To control for this, we repeated the correlation analyses with a percentile bootstrap method (Wilcox & Muska, 2001; Wu, 1986). Specifically, we created a new sample by bootstrapping the current dataset (i.e., sampling with replacement), and calculated the correlation coefficient using the new sample. The procedure was repeated 10,000 times. The resulting correlation coefficients were pooled as an estimate of the distribution of the true correlation coefficient while controlling for heteroscedasticity. In all experiments, the original correlation coefficient was close (~0.06 SD) to the central tendency statistics of the distribution (Table 2), suggesting that the heteroscedasticity had little effect on the reported correlation analysis. Specifically, when we used the mean of the distribution to replace the original correlation coefficient in the statistical analysis, the resulting p-values (Experiment 1–7: $P = 0.038$, $P = 0.050$, $P > 0.17$, $P = 0.021$, $P = 0.036$, $P = 0.076$, $P = 0.016$; Experiment 1–6 combined: $P < 0.001$) were similar to the original p-values (Experiment 1–7: $P = 0.034$, $P = 0.052$, $P > 0.17$, $P = 0.033$, $P = 0.035$, $P = 0.071$, $P=0.018$; Experiment 1–6 combined: $P < 0.001$).

Lastly, we also aimed to rule out the possibility that the ERIAM effect was due to a generalized inability to deal with interference. For example, participants with bigger difficulties dealing with conflict interference may also be more susceptible to impairment of WM due to errors (i.e., ERIAM). However, there was no significant correlation between the flanker accuracy interference effect and ERIAM in any of the seven experiments ($P > 0.46$, $P > 0.76$, $P > 0.80$, $P > 0.79$, $P > 0.75$, $P > 0.32$ and $P > 0.64$). The Bayes factors (alternative over null hypothesis) were 0.14, 0.11, 0.11, 0.11, 0.11, 0.17 and 0.12, respectively, indicating moderate evidence favoring the null hypothesis of no correlation (Lee & Wagenmakers, 2014).

Discussion

The current study consists of seven experiments that consistently demonstrate that action errors impair concurrently active working memory representations, even when those representations are irrelevant to the response conflict task itself. This is the first demonstration of an impairment of ongoing, active cognitive processing due to error commission – an effect we term “error-related impairment of active working memory” (ERIAM).

While all seven studies showed a numerical ERIAM effect at the group level, only the arrow version of the Flanker task (Experiments 1, 2, and 7) consistently produced a strong enough effect to produce a significant ERIAM across the entire sample – at least using the current task design. However, Experiment 6 showed that other conflict tasks can also produce significant group-level ERIAM when the load is sufficient high. Moreover, one related pattern of results was strikingly similar across all seven experiments: ERIAM most affected subjects for whom the WM aspect of the task was more challenging. This was evident from the reliable cross-subject correlation between overall WM accuracy and ERIAM, which was significant in five out of the six individual samples in the verbal WM tasks (overall correlation: $r = -0.41$, $p < 0.001$, Fig. 4), with the non-significant correlation in Experiment

3 showing the same directionality and a p of .17. The non-verbal WM task in Experiment 7 yielded the same correlation as well. This shows that errors consistently produce non-selective impairments of WM maintenance across all tasks when the WM aspect of the task is sufficiently difficult. The likely explanation for this finding is that subjects with a lower overall WM accuracy maintain less stable WM representations, which are then more susceptible to the impairing effects of errors. Conversely, this finding raises the interesting possibility that errors may actually produce an increase in WM accuracy for highly stable WM contents. Indeed, there is a distinct possibility that WM contents that survive the initial broad inhibition that is purported by the AOT are subject to increased maintenance as part of the subsequent adaptive processes that follow the initial inhibitory phase. However, this necessitates further study. In summary, while Experiments 5 and 6 show that response conflict tasks of the non-arrow Flanker variety will produce significant ERIAM on the group level with a sufficiently challenging WM load, it does appear somewhat safe to conclude that arrow Flanker tasks do result in qualitatively stronger ERIAM overall, as they result in significant group-level ERIAM even with less challenging loads (Experiments 1, 2, 6, and 7). While more research is necessary to warrant definitive conclusions, it is possible that aspects of the arrow version of the Flanker task make ERIAM especially likely. For example, both the WM task and the arrow Flanker task require a discrimination between concurrently presented and competing stimuli (the individual letters of the string in the WM task, and the flankers and targets in the arrow Flanker task). This could explain why ERIAM is especially likely in arrow versions of the Flanker task, as both aspects of the task may draw upon similar processes.

Importantly, Experiments 1 and 3 consistently demonstrated that ERIAM effect is not attributable to response conflict. While this is seemingly at odds with a previous study by Kiyonaga & Egner (Kiyonaga & Egner, 2013), which demonstrated working memory impairments when incongruent color stimuli were presented in the delay period between two color words (the “WM Stroop effect”), the stimulus material in the delay period of our tasks did not directly compete with the active WM representation. Hence, in line with the predictions from the adaptive orienting theory of error processing, we here show that errors, and not conflict alone, lead to a broad impairment of entirely task-unrelated WM contents.

It is notable that the ERIAM effect was evident regardless of the duration of the inter-trial interval (ITI) – including at a very long ITI of 2,300ms. This indicates that once working memory has been impaired after action error commission, it cannot be recuperated, even when there is ample time to process the error itself. In that respect, it is helpful to note that the study that lead to the formulation of the influential bottleneck account of post-error processing (Jentzsch & Dudschig, 2009) showed that post-error decreases in accuracy on the same task – i.e., the effect that is indicative of the purported processing bottleneck after errors – reverse into post-error increases in accuracy already at an ITI of 1,000ms (which is less than half the duration of the ITI in the current study). While the exact crossover point at which an ITI is long enough to accommodate a potential bottleneck is likely task-dependent and subject to interindividual variance (Ullsperger, Danielmeier, & Jocham, 2014) the current study shows that the ERIAM effect is observable even at very long ITIs (and indeed increases in effect size with longer RSIs, cf., Experiments 1 and 2), which is somewhat unexpected under a bottleneck account.

Another interesting, related feature of the current dataset is that for all tasks, errors did not lead to consistent increases in post-error accuracy (Danielmeier & Ullsperger, 2011; Ullsperger et al., 2014) or decreases in post-error conflict interference (King, Korb, von Cramon, & Ullsperger, 2010; Ridderinkhof, 2002). This is surprising, especially since at long ITIs, all three conflict paradigms used in the current study typically do show such post-error increases in accuracy and reductions of interference (at least when no concurrent WM load is present). However, some clues come from Maier and Steinhauser (Maier & Steinhauser, 2017), who observed that the presence of a concurrent WM load does alter the neural processing of errors themselves (also see Miller, Watson, & Strayer, 2012). Another possible explanation for this outcome is that participants may actually recognize the impairment of their WM trace after action error commission, perhaps triggering the same performance-monitoring processes that are deployed after motoric errors, again resulting in a processing bottleneck during which the motoric and the WM error draw upon the same set of resources. However, this bottleneck account is contradicted by the data. It would predict a tradeoff between conflict task performance (e.g., the conflict interference effect) and WM performance. However, four out of six experiments in the current study showed a null effect when comparing conflict interference between WM-correct and WM-error trials (this analysis is impossible for Experiment 7, which did not involve a binary error/correct quantification of WM). Moreover, in the two tasks that did show a significant difference, WM-error trials actually showed less conflict interference, rather than more. In summary, while our study targeted the directional influence of errors on WM, the reverse influence should be subject of additional study.

While our results confirm a very concrete hypothesis from the wider theoretical network of the adaptive orienting theory, further testing is also necessary to investigate whether ERIAM itself results from an inhibitory mechanism (as predicted by the AOT) or, alternatively, indeed from a processing bottleneck. Three pieces of evidence lead us to prefer the AOT prediction of an inhibitory effect. First, as mentioned before, there was no increase in conflict interference in trials with WM errors, which one would expect under the bottleneck assumption. Indeed, if anything, the opposite was the case. Second, longer RSIs appeared to increase the ERIAM effect, as mentioned above. Third, indirect evidence for the inhibitory proposition of the AOT comes from the fact that the same type of WM accuracy decrement that is observed in the current study can be observed after the occurrence of unexpected perceptual events in the delay period (Wessel et al., 2016). Since the processing of unexpected events shares an underlying neural network with error processing (Gentsch, Ullsperger, & Ullsperger, 2009; Wessel, Danielmeier, Morton, & Ullsperger, 2012), which includes brain areas commonly involved in inhibitory control (Wessel & Aron, 2017), our preferred interpretation is along those lines. While we do believe that the presence of ERIAM in Experiments 2, 4, 6, and 7 all of which featured a comparatively long ITI, are partially incommensurate with the bottleneck theory, this is not a direct test. Moreover, while the AOT and the bottleneck theory differ in regards to the underlying mechanistic propositions, they share many predictions about post-error effects on overt behavior, such as the existence of ERIAM itself. Hence, neuroscientific studies are necessary to investigate whether inhibitory brain regions are indeed related to ERIAM, similar to what has been found for unexpected perceptual events (Wessel et al., 2016), or whether another mechanism is responsible. Moreover, behavior alone does not allow any inferences about whether the ERIAM effect is due to a direct suppression of the WM contents after errors, or due to a disengagement of attentional processes from their ongoing maintenance. The latter prediction is shared by both the original orienting theory (Notebaert et al., 2009) and the adaptive orienting theory that was derived from it (Wessel, 2018). However, it is unclear whether the initial inhibitory post-error activity purported by the AOT only entails an inhibition of the attentional engagement with the contents of WM, or whether a direct inhibition of the contents themselves takes place. Recent advances in the ability to decode the representational strength of specific contents of WM using scalp electroencephalography (Adam et al., 2020; Kikumoto & Mayr, 2020) will be paramount in offering such mechanistic insights.

Beyond their theoretical relevance for the basic science of error processing, these results have clear-cut applied and clinical relevance. Knowing that erroneous actions in one task affect unrelated cognitive representations in another task provides highly relevant insights into multi-tasking research that informs user-interface design, especially in highly critical situations that require simultaneous motoric and mnemonic work (such as an air traffic controller memorizing multiple flight paths while interacting with a radar console). Moreover, much is known about the impairments in error processing that result from lesions to specific brain networks (Fellows & Farah, 2005; Seifert, von Cramon, Imperati, Tittgemeyer, & Ullsperger, 2011; Stemmer, Segalowitz, Witzke, & Schönle, 2004; Swick & Turken, 2002). The ERIAM phenomenon is highly relevant when treating such patients, especially as they navigate everyday situations that involve holding information in working memory while performing a motor task (e.g., following a set of novel directions while operating motor vehicle). Moreover, the systematic relationship between error processing and working memory maintenance outlined here could also help explain why the training of performance-monitoring processes improves working memory (e.g., Horowitz-Kraus & Breznitz, 2009), and informs the more general relationship between working memory and motor control (e.g., Baddeley, Chincotta, & Adlam, 2001).

In summary, we here provide the first report of a novel behavioral phenomenon, the error-related impairment of active working memory representations (ERIAM). These findings are in line with the specific predictions made by a recent theory of error processing (the adaptive orienting theory), and provide a new empirical framework to test mechanistic hypothesis about how post-error processes interact with working memory.

Context of the research

The current study tests a direct prediction derived from our adaptive orienting theory of error processing (AOT, Wessel, 2018). The specific prediction that errors in motor tasks could lead to adverse effects on concurrent active cognitive processes is a logical extension of the same findings that motivated large parts of the AOT: First, the processing of errors and unexpected events share a common brain network (Wessel et al., 2012). Second, this brain network involves a neural mechanism for inhibitory control (Wessel & Aron, 2013). Third, this inhibitory mechanism can affect both working memory and attentional engagement (Wessel et al., 2016; Soh & Wessel, 2020). Hence, if errors trigger the same processes as unexpected events, and if unexpected events trigger inhibitory processes that can broadly affect cognitive processes, one would indeed expect ERIAM. In future work, we will use the paradigms developed here together with neuroscientific techniques that directly measure the strength of cognitive representations (such as task files or working memory contents, Kikumoto & Mayr, 2020; Adam et al., 2020) or attentional engagement (Muller et al., 1998; Soh & Wessel, 2020) in the brain. Specifically, we aim to test whether the error-related reductions of WM that constitute the ERIAM effect are due to suppressive effects on the WM representation itself, or on the attentional engagement with said representations. We hope that this and other future work will enable mechanistic insights into the precise neural dynamics underlying effects like ERIAM.

Acknowledgements

The authors would like to thank the Cognitive Control Collaborative (in particular, Eliot Hazeltine, Kai Hwang, & Yao Guan) and the Human Perception & Performance group (in particular, Andrew Hollingworth, Cathleen Moore, & Toby Mordkoff) at the University of Iowa for helpful feedback and suggestions. The authors would also like to thank Iman Noferesti for help with data collection. This work was funded by a grant from the National Institutes of Health (R01 NS102201) to JRW.

Data availability.

All data, code, and procedures are available at https://osf.io/3bygv/.

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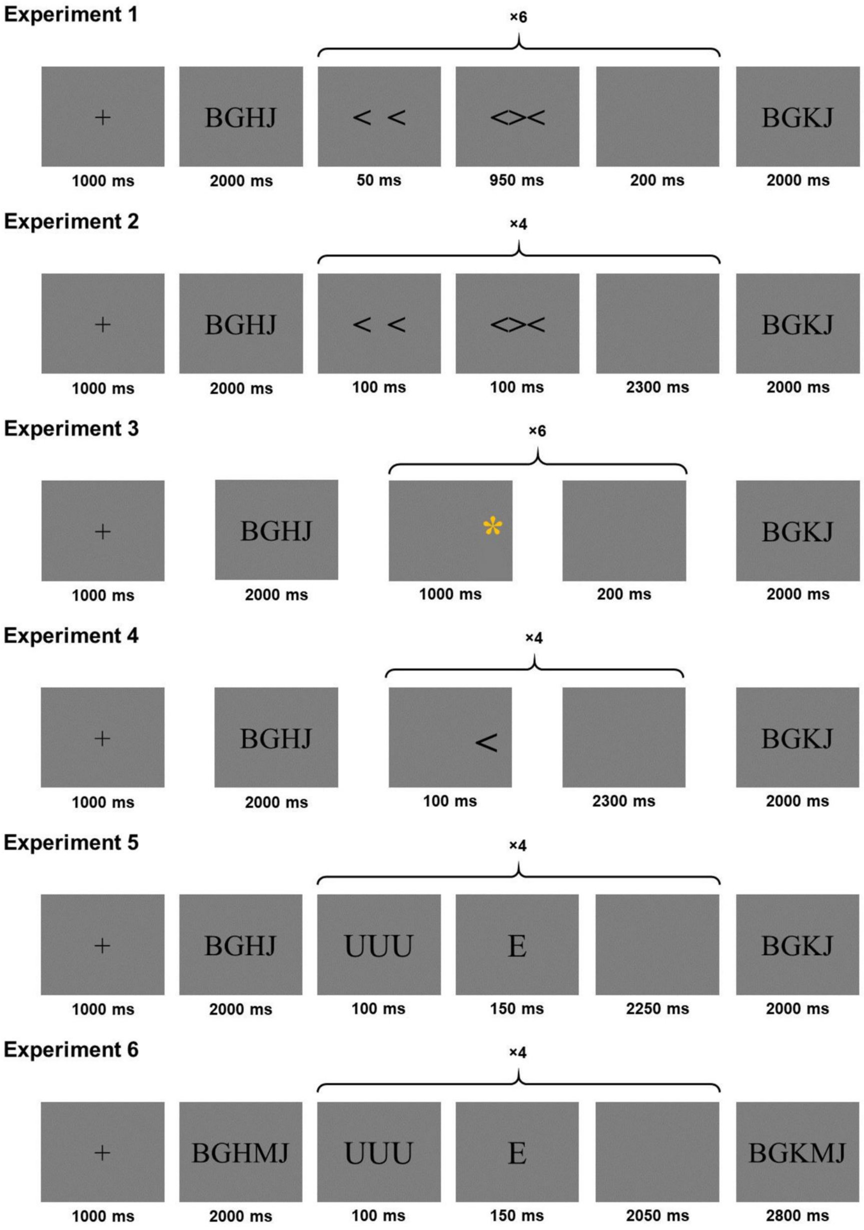

Figure 1.

Trial structure schematics for all experiments.

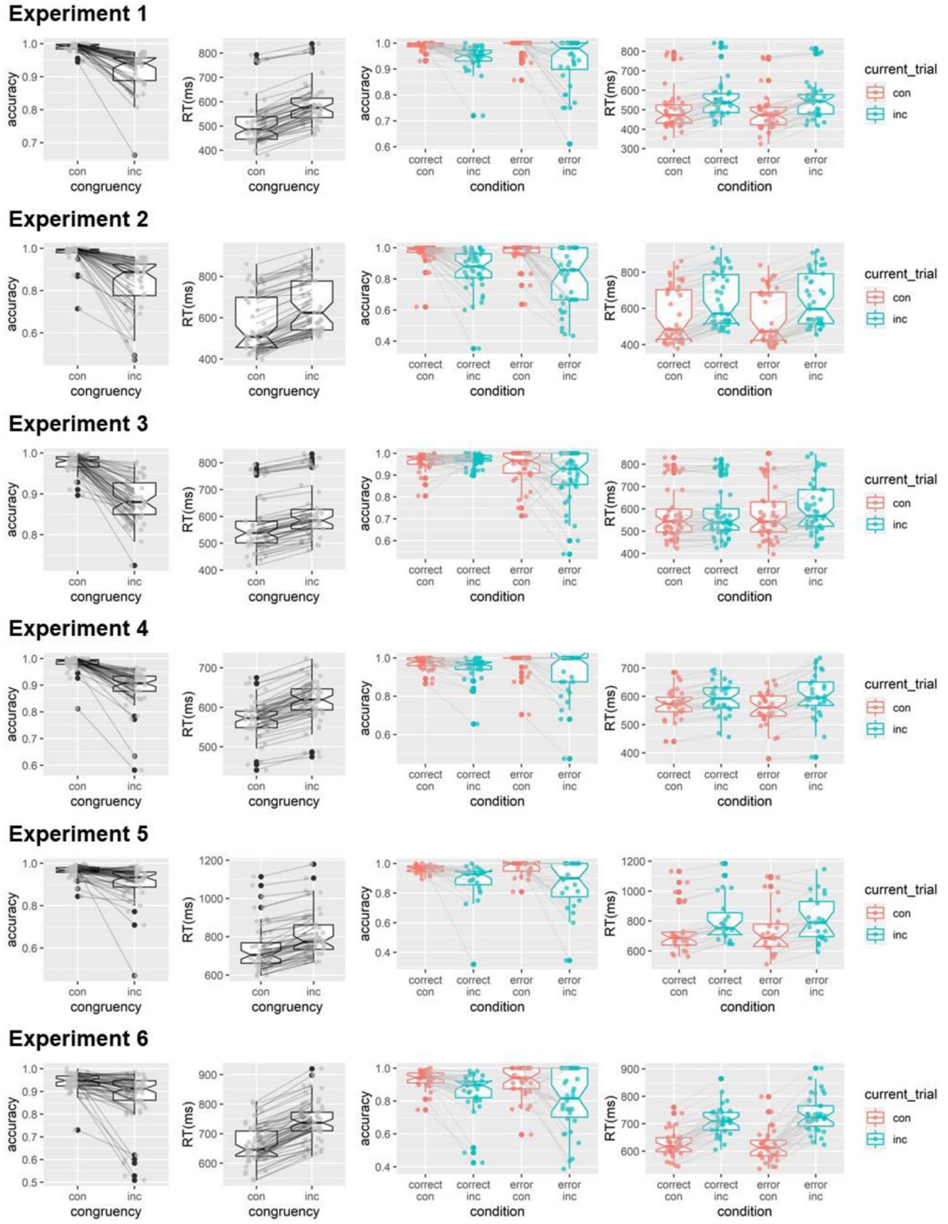

Figure 2.

Conflict task performance across all experiments. From left to right: Conflict task accuracy and mean RT plotted as a function of congruency conditions, and accuracy and mean RT plotted as a function of current trial congruency and previous trial correct/error. Grey lines in box plots connect data from the same participant. Con: congruent; Inc: incongruent. For plots on the right two columns, correct and error corresponds to the previous trial and con and inc indicate the congruency at the current trial.

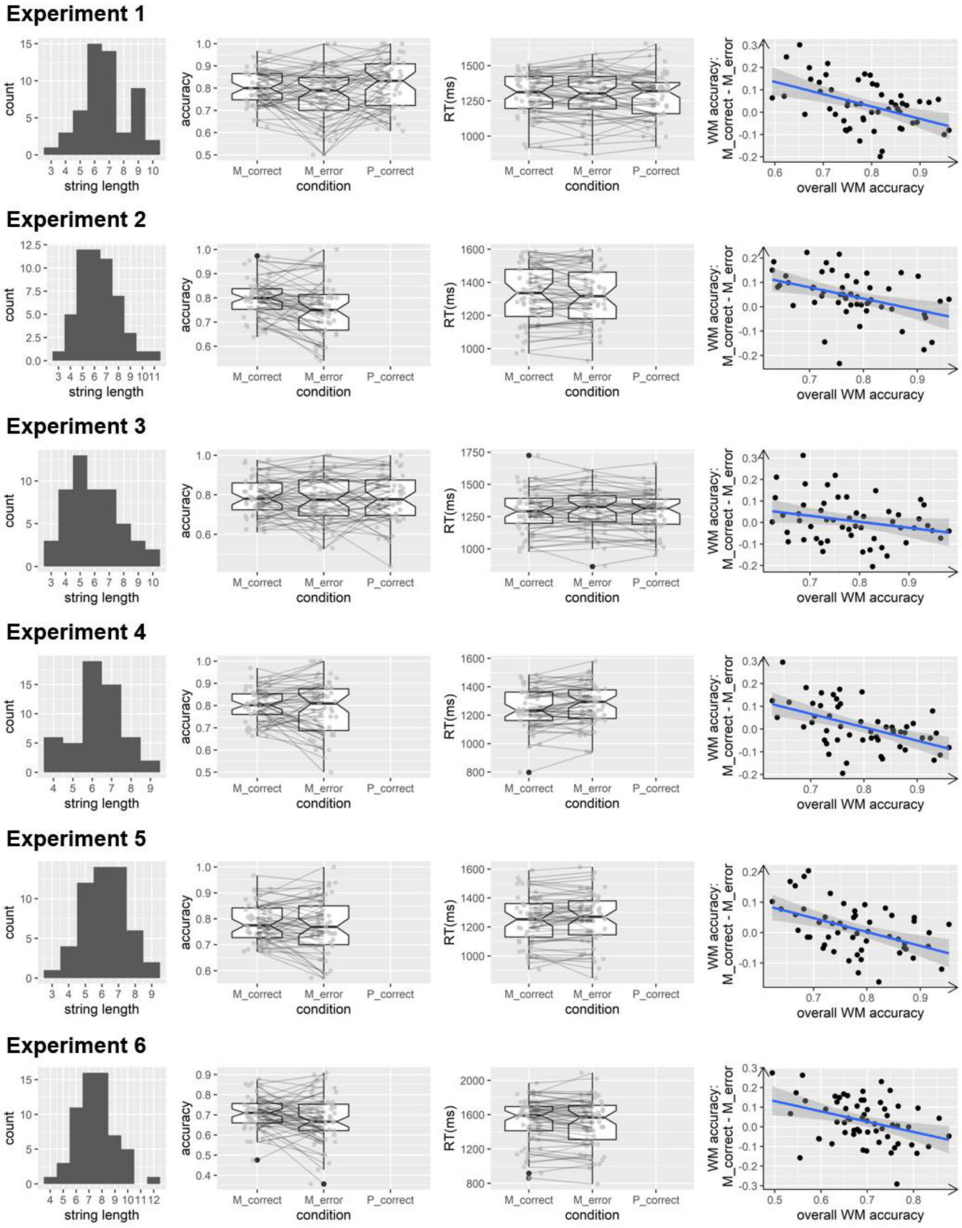

Figure 3.

Working memory performance across all experiments. From left to right: Histogram of WM load, box plots of WM accuracy and RT as a function of experimental condition and scatterplot between overall WM accuracy and ERIAM. Grey lines in box plots connect data from the same participant. M_correct: Mixed-correct; M_error: Mixed-error; P_correct: Pure-correct.

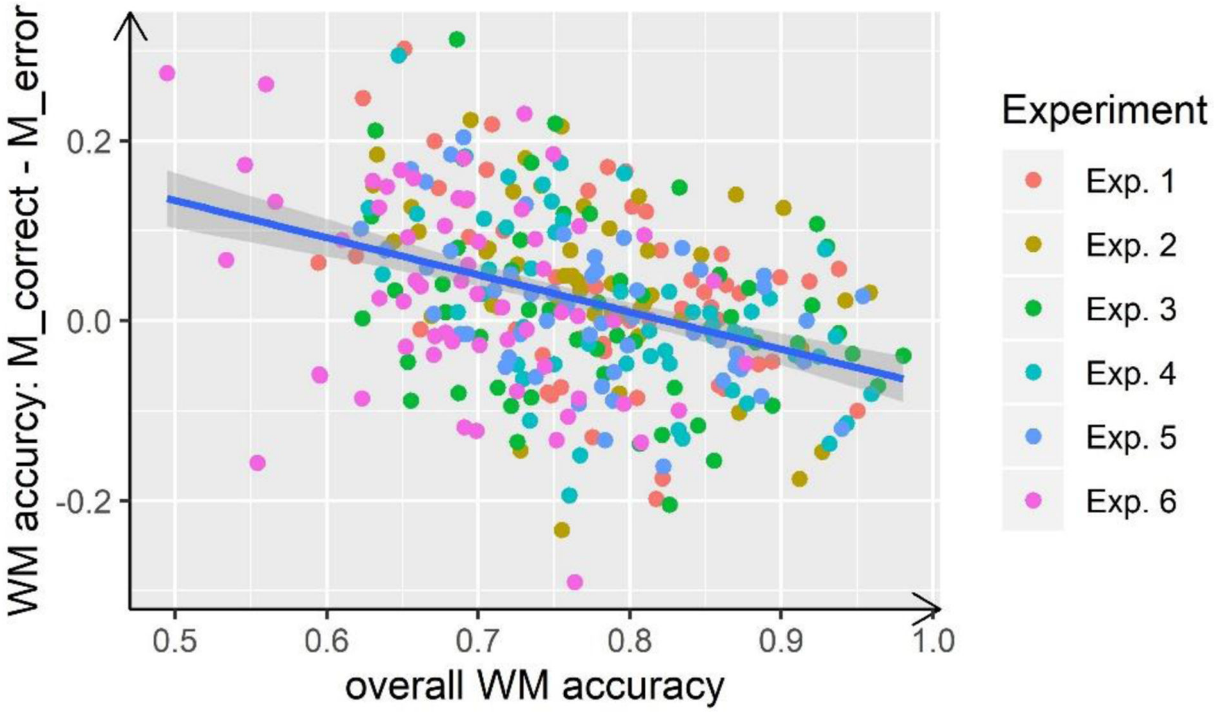

Figure 4.

Scatterplot between overall WM accuracy and ERIAM across experiments. Data from different experiments were coded in different colors. Trend line represents data collapsed across all experiments.

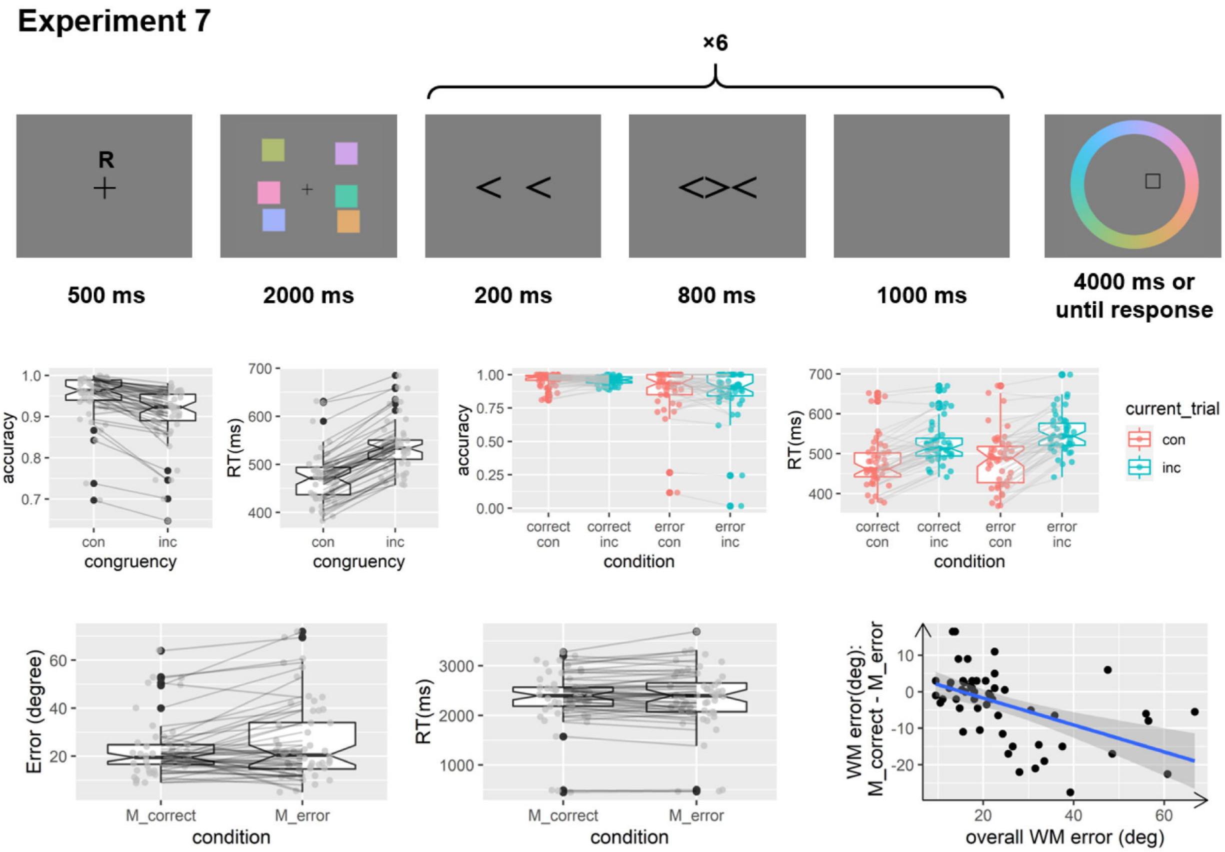

Figure 5.

Experiment 7. Top row: Trial structure schematics. Middle row: Conflict task performance. From left to right: Conflict task accuracy and mean RT plotted as a function of congruency condition, and accuracy and mean RT plotted as a function of current trial congruency and previous trial correct/error. Grey lines in box plots connect data from the same participant. For plots on the right two columns, correct and error corresponds to the previous trial and con and inc indicate the congruency at the current trial. Bottom row: Working memory performance. From left to right: Box plots of WM accuracy and RT as a function of experimental condition and scatterplot between overall WM error and ERIAM. Grey lines in box plots connect data from the same participant. Con: congruent; Inc: incongruent. M_correct: Mixed-correct; M_error: Mixed-error.

Table 1.

Summary statistics of behavioral data across Experiments 1–6.

Conflict task						
Accuracy	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Exp. 4**	**Exp. 5**	**Exp. 6**
Congruent	0.99 (0.002)	0.98 (0.006)	0.98 (0.003)	0.98 (0.004)	0.96 (0.004)	0.94 (0.005)
Incongruent	0.92 (0.008)	0.84 (0.017)	0.88 (0.007)	0.89 (0.010)	0.91 (0.012)	0.88 (0.015)
Post-correct	0.97 (0.005)	0.91 (0.014)	0.97 (0.003)	0.96 (0.009)	0.92 (0.016)	0.89 (0.015)
Post-error	0.96 (0.010)	0.87 (0.018)	0.92 (0.011)	0.95 (0.017)	0.91 (0.018)	0.86 (0.019)
Post-correct interference	−0.04 (0.008)	−0.12 (0.019)	0.01 (0.006)	−0.03 (0.010)	−0.09 (0.030)	−0.08 (0.019)
Post-error interference	−0.06 (0.016)	−0.16 (0.027)	−0.05 (0.017)	−0.06 (0.016)	−0.11 (0.038)	−0.12 (0.033)
WM-correct interference	0.11 (0.011)	0.14 (0.015)	0.14 (0.010)	0.11 (0.009)	0.05 (0.011)	0.06 (0.011)
WM-error interference	0.11 (0.012)	0.17 (0.017)	0.16 (0.014)	0.10 (0.012)	0.05 (0.014)	0.06 (0.013)
RT (ms)	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Exp. 4**	**Exp. 5**	**Exp. 6**
Congruent	511 (13)	565 (19)	569 (14)	569 (6)	739 (16)	664 (8)
Incongruent	588 (12)	657 (18)	613 (14)	617 (7)	806 (16)	740 (8)
Post-correct	524 (17)	601 (24)	576 (17)	581 (11)	772 (33)	669 (8)
Post-error	515 (17)	596 (23)	589 (17)	580 (13)	775 (33)	677 (9)
Post-correct interference	55 (3)	84 (5)	2 (2)	23 (3)	77 (9)	84 (6)
Post-error Interference	61 (7)	96 (7)	27 (7)	48 (7)	76 (19)	115 (11)
WM-correct interference	73 (3)	92 (5)	34 (2)	48 (3)	69 (6)	76 (4)
WM-error interference	73 (4)	88 (6)	39 (3)	50 (3)	63 (5)	80 (4)
WM task						
Accuracy	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Exp. 4**	**Exp. 5**	**Exp. 6**
Pure-correct	0.81 (0.015)	NA	0.78 (0.017)	NA	NA	NA
Mixed-correct	0.80 (0.011)	0.80 (0.011)	0.79 (0.013)	0.80 (0.010)	0.78 (0.010)	0.71 (0.010)
Mixed-error	0.77 (0.017)	0.76 (0.016)	0.78 (0.017)	0.79 (0.017)	0.77 (0.015)	0.68 (0.015)
RT (ms)	**Exp. 1**	**Exp. 2**	**Exp. 3**	**Exp. 4**	**Exp. 5**	**Exp. 6**
Pure-correct	1282 (23)	NA	1283 (27)	NA	NA	NA
Mixed-correct	1294 (21)	1322 (24)	1295 (22)	1251 (20)	1251 (23)	1524 (34)
Mixed-error	1290 (23)	1316 (23)	1304 (23)	1274 (19)	1259 (25)	1507 (36)

Note: Statistics reported are group means and SEMs (between parentheses). Note that post-error analysis in conflict task had smaller sample sizes than other analysis due to constrains on trial counts (see Method). NA: not applicable.

Table 2.

Summary statistics of bootstrapped distributions of correlation coefficient between WM performance and ERIAM effect. SD is reported to show the relative difference between the original correlation coefficient and the central tendency statistics.

	Exp. 1	**Exp. 2**	**Exp. 3**	**Exp. 4**	**Exp. 5**	**Exp. 6**	**Exp. 7**
Original r	−0.458	−0.419	−0.257	−0.512	−0.472	−0.367	−0.516
Mean	−0.456	−0.421	−0.254	−0.511	−0.468	−0.361	−0.520
Median	−0.462	−0.424	−0.260	−0.517	−0.474	−0.368	−0.522
SD	0.095	0.116	0.105	0.096	0.093	0.130	0.093

Table 3.

Summary statistics of behavioral data in Experiment 7.

<table>
<tr><th colspan="6">Conflict task: Accuracy</th></tr>
<tr><th>Congruent</th><th>Incongruent</th><th>Post-correct</th><th>Post-error</th><th>Post-correct interference</th><th>Post-error interference</th></tr>
<tr><td>0.95 (0.008)</td><td>0.91 (0.010)</td><td>0.96 (0.005)</td><td>0.88 (0.025)</td><td>−0.007 (0.006)</td><td>−0.02 (0.014)</td></tr>
<tr><th colspan="6">Conflict task: RT (ms)</th></tr>
<tr><th>Congruent</th><th>Incongruent</th><th>Post-correct</th><th>Post-error</th><th>Post-correct interference</th><th>Post-error interference</th></tr>
<tr><td>472 (7)</td><td>539 (7)</td><td>501 (8)</td><td>517 (8)</td><td>51 (4)</td><td>67 (6)</td></tr>
<tr><th colspan="3">WM task: Error (deg)</th><th colspan="3">WM task: RT (deg)</th></tr>
<tr><th colspan="2">Mixed-correct</th><th>Mixed-error</th><th colspan="2">Mixed-correct</th><th>Mixed-error</th></tr>
<tr><td colspan="2">22.6 (1.6)</td><td>25.8 (2.3)</td><td colspan="2">2347 (80)</td><td>2343 (87)</td></tr>
</table>

Note: Statistics reported are group means and SEMs (between parentheses). Note that post-error analysis in conflict task had smaller sample sizes than other analysis due to constrains on trial counts (see Method).