



Partial repetition between action plans delays responses to ideomotor compatible stimuli

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Received: 18 July 2020 / Accepted: 8 February 2021

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Abstract

Often one must depart from an intended course of events to react to sudden situational demands before resuming his or her original action retained in working memory. Retaining an action plan in working memory (WM) can delay or facilitate the execution of an intervening action when the action features of the two action plans partly overlap (partial repetition) compared to when they do not overlap. We investigated whether partial repetition costs (PRCs) or benefits (PRBs) occur when the intervening event is an ideomotor-compatible stimulus that is a biological representation of the response required by the participant. Participants viewed two visual events and retained an action plan to the first event (A) while executing a speeded response to the second, intervening event (B). In Experiment 1A, the two visual events were ideomotor compatible, non-ideomotor compatible (abstract), or one was ideomotor compatible, and the other abstract. Results showed PRCs for all event A–B stimulus combinations with reduced PRCs for intervening, ideomotor compatible events. In contrast to previous research, there was no evidence that ideomotor-compatible actions were automatic and bypassed the selection bottleneck. Experiment 1B confirmed PRCs for ideomotor compatible stimuli that more accurately mimicked the required response. Findings suggest that mechanisms for activating, selecting, and retaining action plans are similar between ideomotor compatible and abstract visual events. We conclude that PRCs occur in response to intervening events when action plans are generated offline and rely on WM, including those for ideomotor-compatible stimuli; but PRBs may be restricted to actions generated online. This conclusion is consistent with the perceptual-motor framework by Goodale and Milner (Trends in Neuroscience 15:22–25, 1992).

Introduction

The ability to coordinate the execution of different action plans is critical for many complex, goal-directed behaviors such as playing hockey, flying an airplane, and performing surgery. Such coordination often requires one to depart from an intended course of events to react to sudden situational demands before resuming his or her original action. For example, a hockey player who has generated an action plan to pass the puck to a teammate may need to execute an intervening action beforehand, e.g., to move around an opponent before the pass can be executed. Research shows

that executing an action to an intervening event (e.g., move “right” around opponent) can be delayed if the elements (feature codes) of this action plan partly overlap with an action plan retained in working memory (e.g., pass puck to teammate on “right”) vs. do not (e.g., pass puck to teammate on “left”). This delay, referred to as a partial repetition cost, suggests that both action plans shared some common feature codes (“right” in this example, Prinz, 1997) and either competed for binding of relevant feature codes (e.g., Hommel, Müsseler, Aschersleben & Prinz, 2001; Stoet & Hommel, 1999) or competed for response selection due to common code confusion (e.g., Fournier, Gallimore, Feiszli, & Logan, 2014b; Fournier, Hansen, Stubblefield, & Van Dongen, 2020; Hommel, 2004, 2005, 2019; Mattson, Fournier, & Behmer, 2012).

Partial repetition costs (PRCs) occur for actions that share a common representational domain (Hommel et al., 2001; Prinz, 1997), but not for actions that do not—even if the actions require similar motor movements (e.g., responses with the same limb, Fournier, Wiediger, & Tadesse, 2015;

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Wiediger & Fournier, 2008; see also Glover, 1999; Glover, Wall, & Smith, 2012). For example, PRCs occur if both actions rely on stimulus identity where the S-R mappings are generated offline (prior to response execution), are newly learned, and rely on working memory—even if these actions do not share the same motor response (e.g., manual and vocal responses; Fournier et al., 2010). In contrast, PRCs do *not* occur if the intervening action is a reach action generated online (during action execution) based on the spatial metrics of the stimulus, without reference to stimulus identity, S-R mappings, or reliance on working memory (e.g., Fournier, Wiediger, & Tadesse, 2015; Wiediger & Fournier, 2008; see also review by Thomaschke, Hopkins & Miall, 2012b). In the latter case, the online action does not rely on access to working memory and hence would not compete with the retained action plan in terms of feature code binding or response selection due to common code confusion. Instead, the shared action features retained in WM could prime motor responses common with the intervening, online action, facilitating its execution (i.e., leading to a partial repetition benefit; PRB). In short, research to date suggests that PRCs occur if the intervening action is generated offline and relies on working memory and PRBs occur if the intervening action is generated online, and hence does not rely on working memory.

We asked whether PRBs or PRCs occur for intervening actions mapped to ideomotor compatible stimuli (stimuli that represent the required response) as these stimuli are often used in operator displays to reduce cognitive load (Proctor & Vu, 2006, 2016; Wickens & Hollands, 2000). An ideomotor-compatible stimulus depicts the perceptual or sensory information representative of the required response and/or the end goal of the response for that stimulus. For example, an arrow pointing to the left or right is ideomotor compatible if it provides directional information relevant to the observer's response (e.g., move a lever to the left or right, respectively; Greenwald, 2003; Maquestiaux, Ruthruff, Defer, & Ibrahime, 2018). Research suggests that ideomotor compatible stimuli can activate their response representations automatically and *offline*, bypassing the selection process (e.g., Greenwald, 1970, 1972, 2003; Hommel, 2009; Maquestiaux et al., 2018) or partially bypassing the selection process (e.g., Lien, McCann, Ruthruff, & Proctor, 2005). Research also suggests that the strength of response activation by an ideomotor compatible stimulus is greater if it represents both the movement type (e.g., such as keypresses with the right index finger) and direction (e.g., across a set of keys) of the required response vs. only the movement direction (e.g., represented by an arrow or a moving dot across a set of keys; e.g., Brass, Bekkering, Wohlschläger, & Prinz, 2000). In the former case, a more complete perceptual representation of the action (i.e., the response means; such as “movement of the right, index finger”) and its goal (i.e., with

the goal here representing a “specific keypress sequence” to be executed as per experimental instructions) is provided by the stimulus. Furthermore, research suggests that simply watching a hand manipulating a tool can automatically activate (prime) the same action in the observer (e.g., Cattaneo, Caruana, Jezzini, & Rizzolatti, 2009; Chivarino, Bugiani, Grandi, & Colle, 2013; Cracco et al., 2018; Greenwald, 1970; Hommel, 2003; Janczyk, Pfister, & Kunde, 2012; Massen & Prinz, 2009; Pfister, Dignath, Hommel, & Kunde, 2013; Rizzolatti, Fogassi, & Gallese, 2001; Shin, Proctor, & Capaldi, 2010).

To date, PRCs have only been observed for intervening actions associated with non-ideomotor compatible stimuli, which are not perceptually representative of their corresponding responses (e.g., a red or green pound sign associated with a specific keypress sequence with the right or left hand), are not overly learned, and hence should impose a demand on working memory (Behmer & Fournier, 2016; Brass, Bekkering, & Prinz, 2001; Greenwald, 1970; Greenwald, 2003; Greenwald & Schulman, 1973; Shin et al. 2010). Thus, if it is true that ideomotor compatible stimuli activate response representations automatically, bypassing or partially bypassing the selection process, we would expect to find PRBs as opposed to PRCs for intervening actions mapped to ideomotor compatible stimuli—especially for those that are biological representations of the required response. Finding PRBs for ideomotor-compatible stimuli would also suggest that PRBs are not restricted to automatic actions executed *online*.

Experiment 1A

The current study used the partial repetition task (e.g., Fournier et al. 2014a, b; Stoet & Hommel, 1999) to determine whether PRBs or PRCs occur when the intervening action is generated from an ideomotor compatible stimulus. Participants saw two, visual events presented in a sequence. At the presentation of the first event (event A), a response to event A was planned and retained in working memory. During this retention period, the second event (event B) appeared, and a speeded response was made to this intervening event. Afterwards, the retained action plan to event A was recalled and executed. The stimulus types assigned to events A and B, respectively were either: ideomotor compatible (ideomotor-C) and ideomotor-C, abstract and ideomotor-C, ideomotor-C and abstract, or abstract and abstract. Action feature overlap between event A and B was manipulated by having the same hand (partial overlap) or different hands (no overlap) execute a series of different keypress responses.

Consistent with past research, we expected to find PRCs when the intervening and retained action were both

generated from abstract stimuli. We also expected to find PRCs when the intervening action was generated from an abstract stimulus and the retained action was generated from an ideomotor-compatible stimulus. In this case, both actions would be represented in working memory: S-R representations for the intervening event would be created and retained in WM and the ideomotor compatible action would be retained in working memory. Because both action plans would rely on working memory, code competition or confusion can occur, which would delay responses to the intervening event. Moreover, we expected to find PRBs when the intervening and retained action were both generated from ideomotor compatible stimuli and when the intervening action alone was generated from an ideomotor compatible stimulus. This latter prediction is contingent on the assumption that ideomotor-compatible stimuli automatically activate actions directly and bypass the selection process.

No plan (no retention) trials were also included to ensure participants retained an action plan during plan (retention) trials. Increased RT and/or error rates for retention compared to no retention trials would indicate participants retained an action plan during retention trials.

Methods

Participants

Thirty-eight undergraduates ($M_{\text{age}} = 19.45$, age range 18–27; 28 female) at Washington State University received optional credit in their psychology courses for participating. Participants had at least 20/40 visual acuity (confirmed using a Snellen chart), were naive to the purpose of the experiment, and gave informed consent. The study was approved by the Washington State University Institutional Review Board (IRB). Data were excluded for seven participants: two who failed to complete the experiment during the session and five who had low recall accuracy (below 80%) for the retained action (event A). Data analysis was conducted on 31 participants ($M_{\text{age}} = 19.48$, age range = 18–27; 24 female). Effect sizes for partial repetition costs were reported to be large in previous studies [e.g., $d_z = \frac{\sqrt{F}}{\sqrt{n}} = \frac{\sqrt{37.31}}{\sqrt{59}} = 0.80$ for the critical pairwise comparison of overlap and no-overlap trials in Fournier et al. (2014b), and $d_z = \frac{\sqrt{18.42}}{\sqrt{18}} = 1.01$ for the same comparison in Exp. 1 of Stoet & Hommel (1999)]. A power analysis suggested a sample size of at least 26 participants was necessary to reach a power of $1-\beta = 0.95$ assuming a large effect size $d_z = 0.80$ of partial repetition costs and comparisons using a 2×4 repeated-measure ANOVA, two-tailed, $\alpha = 0.05$. The power analysis was performed with G*Power (version 3.1.9.4; Faul, Erdfelder, Buchner, & Lang, 2009).

Apparatus

Stimuli were presented on a 17" CRT monitor, approximately 50 cm in front of the participant. Responses to the retained (stimulus A) and intervening (stimulus B) events were recorded using a custom response keyboard (X-Keys XK80 USB Keyboard, Williamston, MI), placed on a desk, centered at the participant's midline. Participants responded using three vertically aligned keys located on the bottom left and bottom right of the keyboard. The horizontal separation between the left and right response keys (center-to-center) was 7 cm. The immediately surrounding keys were blocked from access with rigid, black key caps. Responses were made with the index fingers of the left and right hands; left-hand responses were executed on the left side of the keyboard and right-hand responses on the right side. Participants rested their index fingers on the left and right center keys before and during each trial. The participant's hands and keyboard were visible when looking down. E-Prime software (version 3.0.3.80 Psychology Software Tools, Inc., Sharpsburg, PA) presented the stimuli and collected data.

Stimuli conditions

For retention trials, participants planned and retained an action to event A while executing a response to event B. The stimulus type (ideomotor compatible or abstract) mapped to event A and event B varied resulting in the following A–B stimulus pairings: ideomotor–C—ideomotor–C, abstract—ideomotor–C, ideomotor–C—abstract, and abstract—abstract. Figure 1 shows examples of the different A–B stimulus types. For no retention (control) trials, the stimulus mapped to event A was always a “< >”, which informed participants to not plan an action, and event B was either an ideomotor compatible or an abstract stimulus. The different responses and stimulus types for events A and B are described separately below. All stimuli for events A and B were enclosed in a white frame (6.8×5.4 cm) with a black border (2 mm) located 5 mm above or below a central fixation cross (3×3 mm). All stimulus images (reported below) filled the white frame.

Event A (retention trials)

Both ideomotor compatible and abstract stimuli required one of four possible responses. Responses comprised a series of three keypresses “center key, upper key, and center key” or “center key, lower key, and center key” with either the left index finger (to the left of body midline) or the right index finger (to the right of body midline).


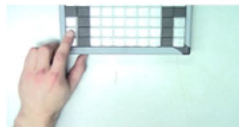


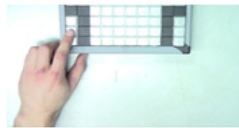

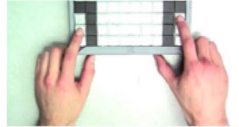





A-B Stimulus Type	Event A (example)	Event B
Ideomotor-C—Ideomotor-C		 OR 
Abstract—Ideomotor-C		 OR 
Ideomotor-C—Abstract		 OR 
Abstract—Abstract		 OR 

Fig. 1 There were four different A–B stimulus types (ideomotor-C—ideomotor-C, abstract—ideomotor-C, ideomotor-C—abstract, and abstract—abstract). For each A–B stimulus type, this figure shows one example of the event A stimulus (right index, upper keypress) and the two possible event B stimuli with which it was paired. Note

that the green and red # are represented in grey and black in black and white version, respectively. Participants retained the action plan to event A while executing an immediate response to event B (color figure online)

Ideomotor compatible stimuli

A 1 s video clip showed two hands with the index fingers initially resting on the center keys of the spatially corresponding column of keys followed by a keypress sequence executed with the left or right index finger. In the video, the left or right index finger pressed its corresponding center key, followed by either the upper or lower key, and then pressed the center key again. Participants planned to reproduce the identical response sequence viewed in the video (e.g., right index finger press center key, upper key, and center key) with their spatially congruent hand (e.g., right index finger press center key, upper key, and center key).

Abstract stimuli

A 1 s video clip showed a number sign [#; 1.2 (width) × 1.6 (height) cm] with an asterisk [1.2 (width) × 1.2 (height) cm] above or below it. The color of the stimuli (red or green) determined which index finger, left or right, would execute the response. The location of the asterisk, above or below the #, indicated the three keypress sequence: the asterisk located *above* the # required a “center key, *upper* key, and center key” response and the asterisk located *below* the # required a “center key, *lower* key, and center key” response. For half of the participants, green stimuli required a right,

index finger response and red stimuli required a left, index finger response; the other half of the participants had the reverse color-index finger mapping.

Event B

Both ideomotor compatible and abstract stimuli required a double keypress of the center key with either the left or right index finger. RTs were based on the completion of the second keypress.¹

Ideomotor compatible stimuli

This consisted of two static images of one hand, left or right, with the first image depicting an index finger keypress on the center key of the spatially corresponding column of keys and the second image representing the index finger resting on the same center key. Each image was presented for 50 ms which provided a rocking hand movement consistent with a keypress. Two, static images were used so that Event B could be briefly presented to encourage speeded responding.

¹ Responses were only defined by execution of the second keypress response in Experiment 1A, and hence RT for the first keypress was not available. However, the first and second keypress RTs were recorded and are reported in Experiment 1B.

Participants executed a double keypress response with their index finger on the center key (e.g., left index finger press center key twice) that was spatially congruent with the image (e.g., left index finger press center key).

Abstract stimuli

This consisted of two static images of either a red # or a green # [1.2 (width) × 1.6 (height) cm]. The image (e.g., a red #) was presented twice for 50 ms to be consistent with the images presented for ideomotor compatible, event B stimuli. Participants executed a double keypress response on the center key with their left or right index finger indicated by the color of the #. The color-index finger response mapping was the same as that assigned to event A when event A was also an abstract stimulus.

Event A (no retention)

On a small number of the trials, event A indicated that no action was to be planned or retained for event A. For these *no retention trials*, event A was a static image of two arrowheads [i.e., < >; 2.7 cm (width) × 1.3 cm (height)] presented for 1 s. Here, no response information for event A was displayed prior to executing the action for event B.

Procedure

Two visual events were presented in a sequence on each trial. For the *retention trials*, participants planned an action to the first event (event A) and retained this action plan in memory. Participants were instructed to not move any body parts (or rely on any external cues) when planning their responses to event A. While retaining this action plan in memory, the second visual event (event B) appeared, requiring an immediate response. For the *no retention trials*, the participants were instructed to not plan or execute a response to event A (< >), but to respond only to event B as quickly and accurately as possible.

Figure 2 shows an example of the trial events for both the retention and the no retention trials. All trials began with an initiation screen which read “press the center keys to start next trial”. When the center keys were pressed simultaneously with the right and left index fingers, the trial started, and a fixation cross (cross) appeared in the center of the screen for 1000 ms. Next, event A appeared above the cross for 1000 ms, followed by the cross alone for 1200 ms. During this time, participants either planned a response to event A (retention trial) or did not (no retention trial). Then, event B appeared below the cross for 100 ms, followed by a blank screen for 1500 ms or until the response to event B was executed. Participants were to

respond as quickly and accurately as possible to event B. After executing the event B response, what occurred next depended on whether the trial required a response to event A (retention) or not (no retention).

On retention trials (Fig. 2, left and center panels), the event B response was followed by a screen that changed (from white) to light grey, signaling participants to execute the event A response. Participants had 2500 ms to execute the event A response. Participants were instructed to execute this response as accurately as possible. After executing the event A response, a blank white screen appeared (500 ms; i.e., the screen changed from light grey back to white). Then RT and accuracy feedback appeared for the event B response (600 ms) and remained present during accuracy feedback for the event A response (350 ms). Afterwards, the initiation screen re-appeared, and participants initiated the next trial when ready.

On no retention trials (Fig. 2, right and center panels), the event B response was followed by a blank white screen (500 ms). Afterwards, the RT and accuracy feedback appeared for the event B response (600 ms). Then, the initiation screen re-appeared, and participants initiated the next trial when ready.

Participants completed one, 90-min session consisting of one practice block and 9 experimental blocks of 48 trials. Each block contained 32 retention trials and 16 no retention trials. For the retention trials, all possible A-B stimulus pairings (within the four A-B stimulus types: ideomotor-C—ideomotor-C, abstract—ideomotor-C, ideomotor-C—abstract, and abstract—abstract) occurred equally often in a random order within each block. For the no retention trials, all possible event B stimuli (for ideomotor compatible and abstract stimulus types) occurred equally often in a random order within each block. During the practice block, a sheet of paper with the S-R mappings for the abstract and ideomotor compatible stimuli was placed on the desk to the right of the participants for reference. A mandatory break of at least 10 s was imposed after block 5, and mandatory breaks of at least 5 s were imposed after all other blocks.

Results and discussion

Partial repetition

To assess the occurrence of partial repetition benefits or costs among our different stimulus types, separate 2 × 4 repeated-measures ANOVAs with the factors of action overlap (no overlap, partial overlap) and A-B stimulus type (ideomotor-C—ideomotor-C, abstract—ideomotor-C, ideomotor-C—abstract, and abstract—abstract) were

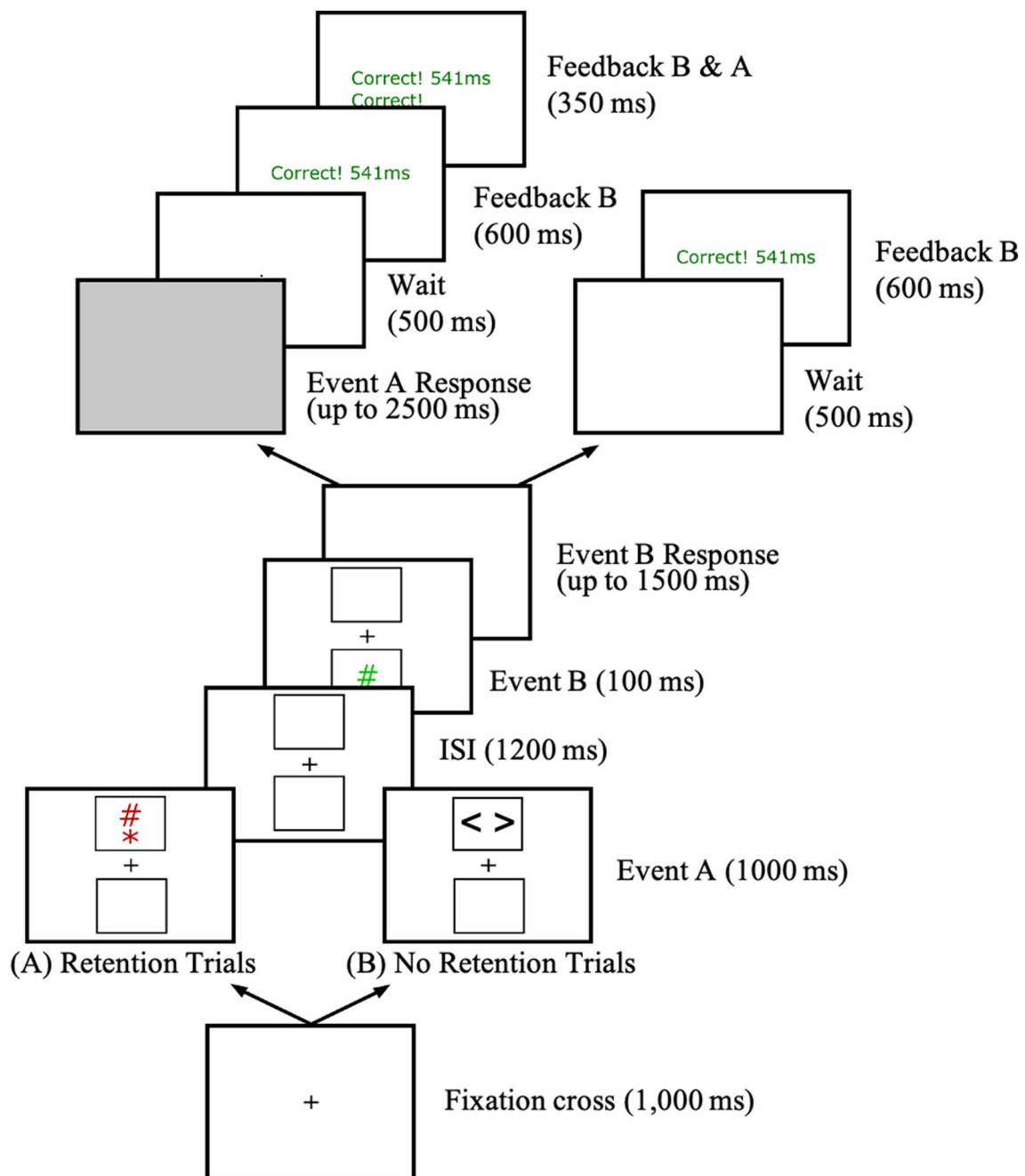


Fig. 2 The trial event sequence for the retention trials (left and center panels) and no retention trials (right and center panels). The A–B stimulus type of abstract—abstract with no overlap is used as an example in the retention trials, and the no retention abstract is used

as an example in the no retention trials. The ISI represents the inter-stimulus interval between event A and event B. See text for description

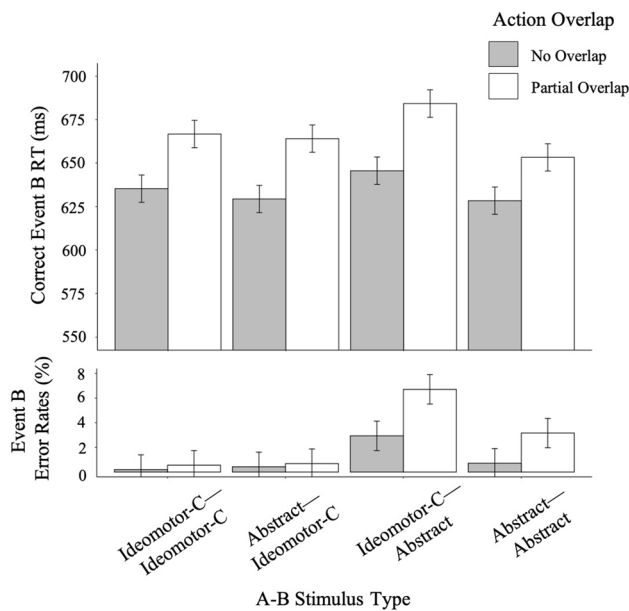


Fig. 3 Experiment 1A. Event B mean correct RT and mean error rates for each A-B stimulus type by action overlap. The error bars represent within-subjects standard errors (Masson & Loftus, 2003). Partial repetition costs (PRCs) were found for all A-B stimulus types

conducted on means for event B correct RTs, event B error rates, and event A error rates.² Event B correct RTs and event B error rates were contingent on accurate responses to event A. Pairwise comparisons were conducted using dependent samples *t*-tests.

Event B RTs

There was a main effect of action overlap [$F(1, 30) = 61.68$, $p < 0.0001$, $\eta_p^2 = 0.67$] and A-B stimulus type [$F(3, 90) = 4.71$, $p = 0.004$, $\eta_p^2 = 0.14$]; the interaction between these factors [$F(3, 90) = 1.14$, $p = 0.338$, $\eta_p^2 = 0.04$] was not significant. Event B RTs were greater for all A-B stimulus types when there was partial overlap ($M = 667$ ms,

$SE = 8.80$) compared to no overlap ($M = 634$ ms, $SE = 8.06$) between event A and event B actions. Thus, partial repetition costs were found for all A-B stimulus types. See Fig. 3 (upper panel). Also, event B RTs were greater for the ideomotor-C—abstract compared to all other A-B stimulus types [$t(30) = 2.48, 3.32$, and 2.67 , $ps < 0.019$, $d = 0.44, 0.60$, and 0.48 for ideomotor-C—ideomotor-C, abstract—ideomotor-C, and abstract—abstract, respectively], which did not significantly differ ($ps > 0.100$). The finding of a switch cost for ideomotor-C—abstract but not for abstract—ideomotor-C (both of which require a switch in stimulus events) suggests that the ideomotor-C event imposed less of a demand on working memory than the abstract event. That is switching to a less demanding event (ideomotor-C) would not necessarily require an update in cognitive effort afforded to the task but switching to a more demanding event (abstract) would—leading to a processing delay (e.g., Braver, 2012; Braver, Reynolds, & Donaldson, 2003).

Event B error rates

There was a main effect of action overlap [$F(1, 30) = 12.58$, $p = 0.001$, $\eta_p^2 = 0.30$], a main effect of A-B stimulus type [$F(3, 90) = 13.71$, $p < 0.001$, $\eta_p^2 = 0.31$], and an interaction between these factors [$F(3, 90) = 4.26$, $p = 0.027$, $\eta_p^2 = 0.12$]. See Fig. 3 (lower panel). For all A-B stimulus types, Event B error rates were greater when there was partial overlap ($M = 2.77\%$, $SE = 0.54$) compared to no overlap ($M = 1.06\%$, $SE = 0.29$) between event A and event B actions. Also, the differences in error rates between the partial overlap and no overlap conditions were larger when event B was abstract (e.g., A-B stimulus types abstract—abstract and ideomotor-C—abstract, $M = 3.11\%$, $SE = 0.84$) compared to ideomotor compatible (A-B stimulus types ideomotor-C—ideomotor-C and abstract—ideomotor-C, $M = 0.31\%$, $SE = 0.18$; $F(1, 30) = 8.56$, $p = 0.006$, $\eta_p^2 = 0.22$). Thus, PRCs were larger when event B was an abstract as opposed to an ideomotor compatible stimulus. Importantly, error rate results suggest that the event B RT interpretations above were not due to a speed-accuracy tradeoff.

Event A error rates

There was only a main effect of action overlap [$F(1, 30) = 4.52$, $p = 0.042$, $\eta_p^2 = 0.13$]; the main effect of A-B stimulus type [$F(3, 90) = 1.26$, $p = 0.294$, $\eta_p^2 = 0.04$] and the interaction between action overlap and A-B stimulus type [$F(3, 90) = 1.92$, $p = 0.131$, $\eta_p^2 = 0.06$] were not significant. Event A error rates were greater when the actions between event A and event B partly overlapped ($M = 11.20\%$, $SE = 0.65$) vs. did not overlap ($M = 8.93\%$, $SE = 0.61$).

² Assessing response accuracy to event A was necessary to ensure participants retained the action plan to the first event in memory while executing their response to the interruption (event B). The response accuracy results for event A have to be interpreted with caution as participant inclusion required that they achieve 80% accuracy. Also, we did not analyze RT for event A for two reasons. First, we asked participants to take their time to respond to event A in order to respond as accurately as possible. They were also told that we were not concerned with how fast they responded to event A, only how accurate they responded. Second, RT for event A was confounded with responses executed to event B. That is, when there was action overlap (i.e., responses to events A and B shared the same response hand), the motor response for event A had to wait for the response to event B to finish before it could start; but when there was no action overlap, the motor response for event A did not necessarily have to wait for the motor response to event B to finish before it could start.

Retention vs. no retention

We examined whether responses in the retention conditions (no overlap and partial overlap) were slower and less accurate than those in the no retention condition. If so, this would provide evidence that participants retained the action plan in WM during retention trials. Trials in which event B was an abstract stimulus and trials in which event B was an ideomotor compatible stimulus were first separated and then analyzed in one-way, repeated-measures ANOVAs with the factor of retention condition (no retention, no overlap, partial overlap). ANOVAs were performed on means for event B correct RTs and event B error rates (contingent on accurate event A trials). Pairwise comparisons were conducted using dependent samples *t*-tests.

When event B was an *abstract stimulus*, the factor of retention condition was significant for RTs [$F(2, 60) = 9.67$, $p < 0.001$, $\eta_p^2 = 0.24$] and error rates [$F(2, 60) = 5.05$, $p = 0.017$, $\eta_p^2 = 0.14$]. RTs for the partial overlap condition ($M = 668$ ms, $SE = 17.21$) were greater compared to the no retention condition [$M = 646$ ms, $SE = 17.17$; $t(30) = 2.85$, $p = 0.008$, $d = 0.51$], but RTs between the no overlap ($M = 637$ ms, $SE = 15.95$) and the no retention condition did not significantly differ [$t(30) = -1.20$, $p = 0.239$, $d = 0.22$]. Also, error rates were no different between the partial overlap ($M = 4.97\%$, $SE = 1.13$) and no retention [$M = 4.61\%$, $SE = 1.26$; $t(30) = 0.26$, $p = 0.799$, $d = 0.05$] conditions, but error rates were greater for the no retention compared to the no overlap condition [$M = 1.77\%$, $SE = 0.53$; $t(30) = 2.99$, $p = 0.005$, $d = 0.54$].

When event B was an *ideomotor compatible stimulus*, the factor of retention condition was significant for RTs [$F(2, 60) = 31.43$, $p < 0.001$, $\eta_p^2 = 0.51$] but not error rates [$F(2, 60) = 1.79$, $p = 0.191$, $\eta_p^2 = 0.06$]. RTs were greater for the partial overlap ($M = 665$ ms, $SE = 17.41$; $t(30) = 6.25$, $p < 0.001$, $d = 1.12$) and no overlap ($M = 632$ ms, $SE = 15.84$; $t(30) = 2.86$, $p = 0.008$, $d = 0.51$) conditions compared to the no retention condition ($M = 613$ ms, $SE = 17.41$).

In general, there was a response cost for the partial overlap and/or no overlap condition(s) compared to the no retention condition. This is consistent with the assumption that participants planned their responses to event A in advance. Otherwise, we should have found no evidence of a cost for retention conditions (partial overlap and no overlap) compared to the no retention condition (e.g., Richardson, Pfister, & Fournier, 2020; Stoet & Hommel, 1999).

Evaluation of whether responses to ideomotor compatible stimuli were automatic

The presence of partial repetition costs found for intervening (event B), ideomotor compatible actions suggest that

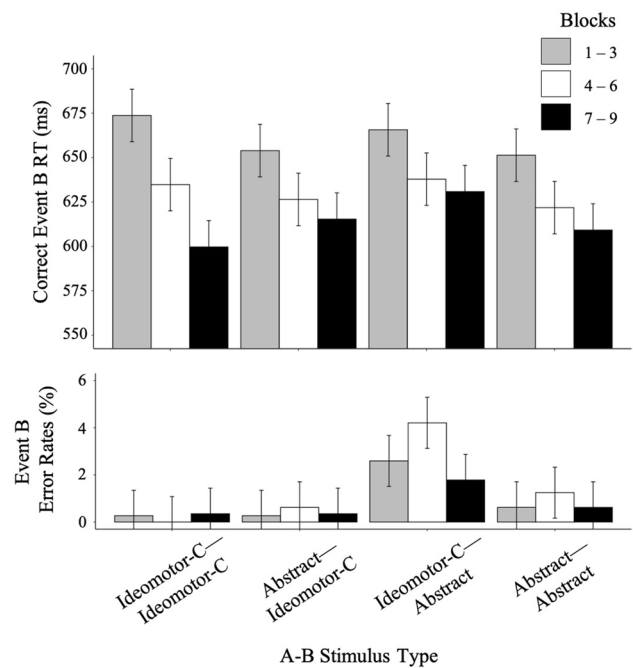


Fig. 4 Experiment 1A. Event B mean correct RT and mean error rates for the no overlap trials only by each A-B stimulus type and block (1–3, 4–6, and 7–9). The error bars represent within-subjects standard errors (Masson & Loftus, 2003). Similar learning effects were found across A-B stimulus types

perhaps responses to ideomotor compatible stimuli were not automatic. To determine whether responding immediately to ideomotor compatible stimuli was automatic (or was more automatic) than responding immediately to abstract stimuli, we evaluated correct RT and error rates for these immediate actions, within the four A–B stimulus types, across blocks. We focused only on trials in which there was no action overlap to eliminate trials in which code competition or confusion may have influenced RTs and error rates. We also parsed blocks into groups of three (blocks 1–3, blocks 4–6, and blocks 7–9) to increase the number of trial RTs per stimulus type contributing to the mean RT. If ideomotor compatible stimuli were indeed responded to automatically or more automatically than abstract stimuli, we would expect an interaction between A–B stimulus type and block suggesting an earlier asymptote in RTs over blocks for ideomotor compatible, event B responses compared to abstract event B responses. Separate A–B stimulus type (4) by block (3) repeated-measures ANOVAs were conducted on means for event B correct RTs and event B error rates for no overlap trials. RTs and error rates were contingent on correctly responding to event A.

Event B RTs

Results showed a main effect of block [$F(2, 60) = 21.02$, $p < 0.001$, $\eta_p^2 = 0.41$], but not A-B stimulus type [$F(3, 90) = 1.78$, $p = 0.173$, $\eta_p^2 = 0.06$]. Moreover, the interaction between A-B stimulus type and block was not significant [$F(6, 180) = 1.63$, $p = 0.141$, $\eta_p^2 = 0.05$]. Figure 4 (upper panel) shows that RTs decreased similarly across blocks for all A-B stimulus types regardless of whether the event B response was mapped to an ideomotor compatible or abstract stimulus. Thus, there was no evidence suggesting that responses to ideomotor-compatible stimuli were automatic or more automatic than responses to abstract stimuli. However, error rate data suggest that response performance was overall better for ideomotor-compatible stimuli.

Event B error rates

Results showed only a significant main effect of A-B stimulus type [$F(3, 90) = 8.44$, $p < 0.003$, $\eta_p^2 = 0.22$]; the main effect of block [$F(2, 60) = 1.74$, $p = 0.184$, $\eta_p^2 = 0.05$] and the interaction between A-B stimulus type and block [$F(6, 180) = 1.32$, $p = 0.272$, $\eta_p^2 = 0.04$] were not significant. Error rates were lower when event B was ideomotor compatible compared (i.e., ideomotor-C—ideomotor-C and abstract—ideomotor-C) to abstract (i.e., ideomotor-C—abstract and abstract—abstract), $t(30) = -3.58$, $p = 0.001$; $d = -0.64$. This suggests response performance was overall better when the intervening action was ideomotor compatible compared to abstract regardless of experience with the task. Figure 4 (lower panel) shows that error rates did not compromise the RT interpretations above.

Summary

Results showed PRCs for all A-B stimulus types regardless of whether the intervening response was mapped to an ideomotor compatible or abstract stimulus. PRCs also occurred regardless of whether the retained (A) and intervening (B) stimulus events were of the same or different stimulus type: ideomotor compatible or abstract. Further, PRCs were reduced (based on error rate) for intervening, ideomotor compatible events compared to intervening abstract events. However, it is possible that our ideomotor-compatible stimuli for event B were not strongly ideomotor compatible to be automatic. In Experiment 1B, we examined if an intervening stimulus that was more visually accurate in representing the required response would also show PRCs.

Experiment 1B

It could be argued that event B, ideomotor compatible stimuli in Experiment 1A were not strongly ideomotor compatible as the finger movement consisted of two static frames that depicted a rocking movement of the index finger on the key. In Experiment 1B, event B was changed to a video mimicking the actual double key press required by the participant. Also, while the index finger of one hand executed the double key press on its spatially corresponding, center key, the index finger of the other hand rested on its spatially corresponding, center key. This video scenario more accurately represented the body movements (and hence action goal) of the response required by participants. We examined whether PRCs would be observed for these ideomotor-compatible stimuli.

Participants

Participant recruitment, compensation, and visual acuity was the same as that described in the previous experiment. Forty-two participants ($M_{\text{age}} = 20.07$, age range = 18–27; 29 female) participated; three participants' data were eliminated due to low event A accuracy (below 80%) and seven participants' data were lost due to a program error. Data analysis was conducted on a total of 32 participants ($M_{\text{age}} = 20.55$; 29 female). A power analysis suggested a sample size of at least 12 participants would be necessary to reach a power of $1 - \beta = 0.95$ when assuming partial repetition costs come with a large effect size of $d_z = 0.80$ and comparisons based on a one-way, repeated-measures ANOVA with three levels, two-tailed, and $\alpha = 0.05$ (G*Power, version 3.1.9.4; Faul et al., 2009). This experiment was approved by the Washington State University IRB, and informed consent was obtained from all participants.

Apparatus, Stimuli and Procedures

These were the same as Experiment 1A except for the following. Event B was a 100 ms video of two hands with one hand (left or right) executing a double key press with the index finger on its corresponding, center key, and the other hand (right or left) resting the index finger on its corresponding, center key. Stimuli for events A and B during retention trials and stimuli for event B during no retention trials were always ideomotor compatible (i.e., one stimulus type = ideomotor-C—ideomotor-C). Also, RT to the first keypress as well as the second keypress to event B was recorded. Participants completed one practice block and five experimental blocks of 32 trials over one, 60 min session.

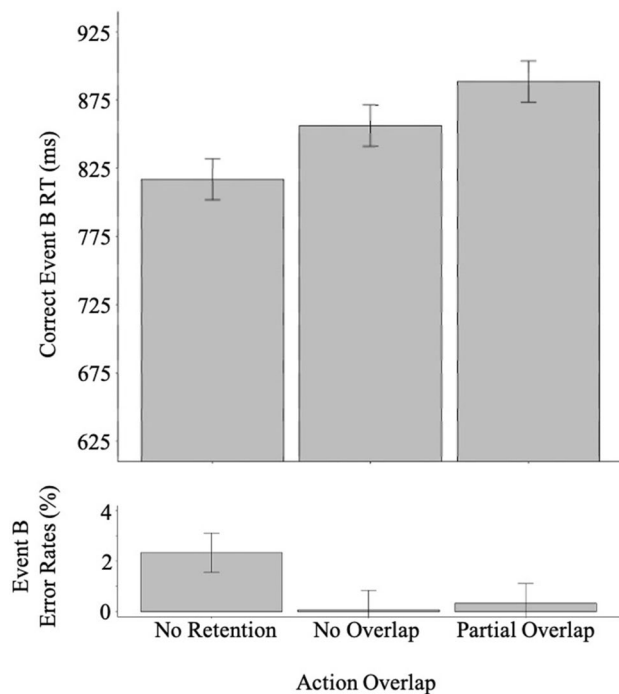


Fig. 5 Experiment 1B. Event B mean correct RT and mean error rates for the conditions of action overlap (no retention, no overlap and partial overlap). The error bars represent within-subjects standard errors (Masson & Loftus, 2003). Partial repetition costs (PRCs) were found for ideomotor compatible stimuli

Each block contained 12 partial overlap, 12 no overlap, and 8 no retention trials. E-Prime software (version 2.0.10.356 Psychology Software Tools, Inc., Sharpsburg, PA) presented stimuli and collected data.

Results and discussion

Partial repetition and retention vs. no retention

One-way, repeated-measures ANOVAs with the factor of action overlap (no retention, no overlap, partial overlap) were conducted separately on means for event B correct RTs, event B error rates, and event A error rates. Event B correct RTs and error rates were restricted to accurate event A trials. A main effect of action overlap was found for event B RTs [$F(2, 62) = 23.44, p < 0.001, \eta_p^2 = 0.43$], event B error rates [$F(2, 62) = 12.76, p = 0.001, \eta_p^2 = 0.29$], and event A error rates [$F(2, 62) = 35.52, p < 0.001, \eta_p^2 = 0.51$]. Pairwise comparisons, conducted using dependent samples t-tests, are described below.

Event B RT and error rates

Figure 5 shows the means for event B RTs³ and error rates. As is evident in Fig. 5, RTs were greater for partial overlap ($M = 889, SE = 23.70$) compared to the no overlap condition [$M = 856, SE = 21.03; t(31) = 4.85, p < 0.001, d = 0.86$] with no difference in error rates [$t(31) = 1.16, p = 0.225, d = 0.21$]. These findings confirm a PRC for ideomotor-compatible stimuli. Also, Fig. 5 shows greater RTs for the partial overlap [$M = 889, SE = 23.70; t(31) = 4.85, p < 0.001, d = 1.01$] and no overlap [$M = 856, SE = 21.03; t(31) = 3.47, p = 0.002, d = 0.61$] conditions compared to the no retention condition ($M = 817, SE = 19.69$). This suggests that participants retained the action plan for event A during the retention trials. However, this difference in RTs may be compromised somewhat by a speed-accuracy tradeoff as there was a higher error rate in the no retention condition compared to the partial overlap [$t(31) = 3.34, p = 0.002, d = 0.59$] and no overlap [$t(31) = 4.00, p < 0.001, d = 0.71$] conditions.

To evaluate the possibility of a speed-accuracy tradeoff, we examined the mean event B error RTs for the different action overlap conditions. Error RTs were slower ($M = 1071$ ms for the no retention, $M = 1128$ ms for the no overlap, and $M = 932$ ms for the partial overlap conditions) compared to correct RTs for all action overlap conditions (see Fig. 5). Importantly, these findings suggest that the higher error rates found for the no retention compared to the no overlap and partial overlap conditions were not based on fast guesses, and hence the correct RT trends reported above were not likely due to a speed-accuracy tradeoff.

Event A error rates

Finally, event A error rates were larger for the partial overlap ($M = 8.13\%, SE = 1.28$) compared to the no overlap condition [$M = 5.34\%, SE = 0.73; t(31) = 2.97, p < 0.006, d = 0.53$] suggesting a cost in recall accuracy due to partial repetition. Also, event A error rates were larger in the partial overlap [$t(31) = 6.24, p < 0.001, d = 1.10$] and no overlap [$t(31) = 7.16, p < 0.001, d = 1.26$] conditions compared to the no retention condition ($M = 0.09\%, SE = 0.09$). This latter finding was expected as error rates for the no retention condition could only consist of slow responses to Event B or anticipatory responses to start the next trial.

In short, the findings above are comparable with the findings and conclusions from Experiment 1A. That is, PRCs,

³ Similar to Experiment 1A, RTs to the second key press are shown. RTs to the first keypress were 161–171 ms faster than the second keypress for all three conditions. RTs to the first keypress were 646 ms, 690 ms, and 718 ms for the no retention, no overlap, and partial overlap conditions respectively.

not PRBs, occurred for our ideomotor-compatible stimulus events.

Evaluation of whether responses to ideomotor compatible stimuli were automatic

We also confirmed, similar to Experiment 1A, that responses to ideomotor-compatible stimuli were not automatic. We evaluated correct event B RTs and error rates for the no overlap and no retention stimulus conditions across the five experimental blocks. If event B RTs were greater in the no overlap vs. no retention condition across all blocks, this would suggest that ideomotor compatible actions are delayed when retaining an action plan which is inconsistent with the assumption of automaticity. Stimulus condition (2) by block (5) repeated-measures ANOVAs were conducted separately on mean correct event B RTs and event B error rates. RTs and error rates were contingent on correctly responding to event A.

Results showed a main effect of the block for RTs [$F(4, 124) = 12.51, p < 0.001, \eta_p^2 = 0.29$] but not error rates ($F < 1$), a main effect of stimulus condition for RTs [$F(1, 62) = 11.64, p = 0.002, \eta_p^2 = 0.27$] and error rates [$F(1, 62) = 14.18, p = 0.001, \eta_p^2 = 0.31$], and no interaction between these factors for RTs ($F < 1$) or error rates ($F < 0$). Importantly, RTs for the no overlap condition were consistently greater than the no retention condition across blocks, and both stimulus conditions continued to decrease to a similar degree across blocks. Correct event B RTs were as follows for the no overlap and no retention stimulus conditions, respectively, across blocks: $M = 916$ ms and $M = 871$ ms for block 1, $M = 876$ ms and $M = 837$ ms for block 2, $M = 841$ ms and $M = 799$ ms for block 3, $M = 835$ ms and $M = 805$ ms for block 4, and $M = 813$ ms and $M = 773$ ms for block 5.

General discussion

We expected that responses to intervening stimulus events that were ideomotor compatible would lead to partial repetition benefits (PRBs), as opposed to partial repetition costs (PRCs), based on the assumption that ideomotor compatible stimuli activate responses directly and automatically, or at least partly automatically. In contrast to our expectations, responses to intervening, ideomotor-compatible stimulus events led to PRCs. However, the magnitude of the PRCs found for ideomotor compatible stimuli was less than that found for non-ideomotor compatible (abstract) stimuli. Together, these findings suggest that the mechanisms for activating, selecting, and retaining action plans were quite similar between ideomotor compatible and abstract visual events.

In contrast to previous research, responses to ideomotor compatible stimuli in this study were not automatic (Cracco et al., 2018; Greenwald, 1970, 2003; Greenwald & Shulman, 1973; Halvorson, Ebner, & Hazeltine, 2013; Heyes, 2011; Maquestiaux et al., 2018) or partly automatic (Lien, Proctor, & Allen, 2002; Lien et al., 2005; Shin et al., 2010). In addition, responses to ideomotor compatible stimuli were not more automatic than responses to our non-ideomotor compatible, abstract stimuli. Results from Experiment 1A showed that RTs to the intervening event decreased with practice to a similar degree across the ideomotor compatible and abstract stimuli. This was surprising given that only the abstract stimuli had an arbitrary S-R mapping—and hence response retrieval time for this condition was expected to benefit more from practice. Also, in Experiment 1B, we found no evidence that ideomotor-compatible stimuli were responded to automatically— even though these stimuli mimicked the required response. Here, responses to ideomotor compatible stimuli were delayed while retaining vs. not retaining an action plan in WM, and this occurred regardless of the amount of practice on the task. Thus, the failure to obtain PRBs for intervening, ideomotor compatible events may be because the responses activated by these stimuli were not automatic and did not bypass or partially bypass the selection process (e.g., Greenwald, 2003; Lien et al., 2002, 2005).

It could be argued that our ideomotor-compatible stimuli were too small in both experiments to be truly representative of the required response and their sensory effects. As a result, these stimuli may not be salient enough to *directly* activate their representational responses and bypass or partially bypass selection. However, Greenwald (1970, 2003) showed that arrowheads were sufficient to automatically (or at least partly automatically) activate manual keypress responses. The intervening events for our ideomotor-compatible stimuli (keypresses with right or left index finger) should have been at least as salient as arrowheads. This was especially true for Experiment 1B which used videos of index finger key presses that were identical to the responses required by participants. Thus, it is more likely that ideomotor-compatible stimuli do not activate their responses directly, bypassing (or partly bypassing) the selection bottleneck. At least there is no evidence in our study that our ideomotor-compatible stimuli did so (see also Sun, Custers, Hans, & Henk, 2020). It is more probable that activation of response representations was stronger for our ideomotor compatible stimuli, and activation of response representations as well as response selection occurred earlier for our ideomotor compatible stimuli than for our abstract stimuli— particularly because responses mapped to our ideomotor compatible stimuli tended to be just as fast but more accurate (with accuracy being close to perfect) compared to responses mapped to our abstract stimuli.

The findings of PRCs and similar practice effects for all of our stimulus sets, regardless of stimulus type, suggest that ideomotor compatible and abstract stimuli events require the same underlying mechanisms when retaining an action plan to one event while executing an action plan to another (e.g., Shin & Proctor, 2012; see also Behmer & Fournier, 2016; Heyes, 2010; Landmann, Landi, Grafton, & Della-Maggiore, 2011; Press et al. 2012). We suggest that responses to ideomotor-compatible stimuli, similar to abstract stimuli, require categorization of the stimuli events into meaningful motor sequences (e.g., Heyes, 2010; Landmann et al., 2011; Press et al., 2012; Valyear & Culham, 2010). Categorization of stimuli into responses is assumed to occur offline and could be subject to interference from other competing actions (e.g., Glover, 2002, 2004; Glover et al. 2012; Hommel, 2009; Passingham & Toni, 2001; Passingham, Toni, & Rushworth, 2000; Thomaschke, Hopkins, & Miall, 2012a, 2012b; Wiediger & Fournier, 2008; Wise, di Pellegrino, & Boussaoud, 1996)—including retained actions. However, it is difficult to determine whether the process of categorically translating stimuli into responses, the demands on WM (or other cognitive control processes), or both accounts for the PRCs obtained for our ideomotor compatible and abstract stimuli events because our ideomotor compatible stimuli did not appear to be processed more automatically than our abstract stimuli (see also findings by Behmer & Fournier, 2016; Press et al., 2012). The smaller PRCs obtained for our ideomotor compatible vs. abstract stimuli (based on error rates) suggest that ideomotor compatible stimuli may impose less of a demand on WM, and decreased demands on WM should reduce the size of PRCs (e.g., Behmer & Fournier, 2014; Fournier et al., 2014a, b). This interpretation is consistent with the extremely low error rates found in response to intervening, ideomotor compatible events vs. abstract events.

To date, PRBs have been found for *online* reach actions (i.e., that do not require categorization of a stimulus into a response). That is, when these actions are executed by the hand one would naturally use to touch a stimulus that remains present until response execution is completed (Wiediger & Fournier, 2008; Fournier et al., 2015). Fournier et al. (2010) also found that PRCs were eliminated when responses to interruptions were highly learned and automatic (i.e., reading a word “left” aloud while retaining a sequence of “left” keypress responses) as opposed when they were not (e.g., reporting aloud the antonym “left” of a word while retaining a sequence of “left” keypress responses). It is possible, however, that Fournier et al. (2010) did not find PRBs due to weak cross-modality priming between the retained and intervening actions because the retained action was a hand response and the intervening action was a vocal response. Thus, it is very possible that responses to interruptions that are highly learned, automatic and executed offline

could result in PRBs if the intervening and retained actions required the same response modality (i.e. allowing for motor priming).

Based on the current literature, whether an interruption leads to PRCs depends on whether the intervening action requires *offline*, stimulus categorization and response selection (associated with ventral stream activation) that is under cognitive control and is not automatic. Also, whether an interruption leads to PRBs depends on whether the intervening action is executed *online* (associated with dorsal stream activation; Gonzalez, Ganel, & Goodale, 2006; Goodale, 2016; Goodale & Humphrey, 1998; Goodale & Milner, 1992; Shin et al., 2010; Wiediger & Fournier, 2008). Online guidance of reach responses invokes automatic visual-control mechanisms that can determine responses based solely on metrics such as spatial relations, and are likely processed via a *direct route* of processing (e.g., Barber & O’Leary, 1997; Eimer et al., 1995; Fournier et al., 2015; Kornblum et al., 1990; Thomaschke et al. 2012a, b; Wiediger & Fournier, 2008). Also, online actions have been shown to occur independent of the processes in which stimulus–response categorization and action planning take place (e.g., Glover, 2002, 2004; Glover et al., 2012; Goodale & Humphrey, 1998; Goodale & Milner, 1992). Thus, online actions should not interact with processes that can lead to code competition or confusion, and hence should not lead to a PRC. The online action account for PRBs can also explain other observations of costs and benefits found between action and action effects (see Thomaschke et al. 2012a, b). To further determine whether PRBs are restricted to online actions (i.e., a metric-based control system), our lab is currently examining partial repetition effects for action events that have extensive S-R training and require the same response modality.

Conclusion

We showed that responding to an intervening event that is perceptually similar to the response (ideomotor compatible) can be delayed if there are shared features between the intervening action and a retained action plan. The action representations associated with ideomotor compatible stimuli, at least those used in the current study, were not fundamentally different from those learned to abstract stimuli. Whether PRBs can occur for highly automatized S-R associations (e.g., those that may at least partially bypass the selection bottleneck) is yet to be determined. Understanding when PRCs or PRBs can occur or be eliminated can provide insight into how actions are represented and how and when they will interact. This has important implications for operator display design, particularly when one must temporarily withhold action to one event to quickly respond to another.

Acknowledgements This work was inspired by experimental data previously collected by James R. Miller in his masters’ thesis. We thank

Iring Koch for his recommendation to cross the ideomotor compatible and abstract stimulus events utilized in Experiment 1A. Finally, we thank Washington State University undergraduates Hannah Jensen and Erin McMeekin for their help with data collection.

Supporting Data for the Current Project This can be accessed at: <https://research.libraries.wsu.edu/xmlui/handle/2376/17908>.

Compliance with ethical standards

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

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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