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Free-choice and forced-choice actions: Shared representations and conservation of cognitive effort

Benjamin Richardson[1] · Roland Pfister[2] · Lisa R. Fournier[1]

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Abstract
We examined two questions regarding the interplay of planned and ongoing actions. First: Do endogenous (free-choice) and exogenous (forced-choice) triggers of action plans activate similar cognitive representations? And, second: Are free-choice decisions biased by future action goals retained in working memory? Participants planned and retained a forced-choice action to one visual event (A) while executing an immediate forced-choice or free-choice action (action B) to a second visual event (B); then the retained action (A) was executed. We found performance costs for action B if the two action plans partly overlapped versus did not overlap (partial repetition costs). This held true even when action B required a free-choice response indicating that forced-choice and free-choice actions are represented similarly. Partial repetition costs for free-choice actions were evident regardless of whether participants did or did not show free-choice response biases. Also, a subset of participants showed a bias to freely choose actions that did *not* overlap (vs. did overlap) with the action plan retained in memory, which led to improved performance in executing action B and recalling action A. Because cognitive effort is likely required to resolve feature code competition and confusion assumed to underlie partial repetition costs, this free-choice decision bias may serve to conserve cognitive effort and preserve the future action goal retained in working memory.

Keyword Feature binding · Action planning · Partial-repetition costs · Action overlap · Free choice · Cognitive effort

Introduction

The ability to coordinate the execution of different action plans is critical for many complex, goal-directed behaviors such as playing hockey, driving a car, and performing surgery. Such coordination often requires that the agent departs from an intended course of events to react to sudden situational demands before resuming his or her original action. For example, a hockey player will frequently generate an action plan to pass the puck to a teammate but will often have to execute an intervening action beforehand, for example, 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") versus 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 & Gallmore, 2013; Fournier, Gallimore, Feiszli, & Logan, 2014; Hommel, 2004, 2005; Mattson, Fournier, & Behmer, 2012).

Although partial repetition costs are robust between forced-choice action plans derived from stimulus identities, it is unclear whether partial repetition costs occur for intervening, free-choice action plans while retaining a forced-choice action plan. If so, this would indicate that the efficiency of free-choice response execution can be influenced by future action goals retained in working memory. Also, it would indicate that

✉ Lisa R. Fournier
lfournier@wsu.edu

Benjamin Richardson
benjamin.richardson@wsu.edu

Roland Pfister
roland.pfister@uni-wuerzburg.de

[1] Department of Psychology, Washington State University, Pullman, WA, USA

[2] Department of Psychology III, University of Würzburg, Röntgenring 11, 97070 Würzburg, Germany

free-choice and forced-choice action plans share similar cognitive representations (feature codes) and hence are represented within the same cognitive domain. Moreover, by examining free-choice actions to an intervening event we can examine if free-choice actions are biased by a future action plan (goal) retained in working memory and whether partial repetition costs (if they occur) are, in turn, influenced by free-choice response biases.

Partial repetition costs 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, & Taddese, 2015; see also Glover, 1999; Glover, Wall, & Smith, 2012; Wiediger & Fournier, 2008). For example, partial repetition costs 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, partial repetition costs do *not* occur between reach responses if one is generated as described above (or is retained in working memory) and the other is generated by stimulus detection where responses rely on spatial metrics of the stimulus generated online (during action execution) without reference to stimulus identity, S-R mappings, or reliance on working memory (e.g., Fournier et al., 2015; Wiediger & Fournier, 2008; for a further exception, see Kunde, Hoffmann, & Zellmann, 2002).

Investigating whether free-choice and forced-choice responses share similar cognitive representations is important because previous studies have claimed that human action control draws on two anatomically separable systems, one system concerned with internally generated or endogenous actions and one system concerned with externally triggered or exogenous actions (e.g., Jahanshahi et al., 1995; Keller et al., 2006; Obhi & Haggard, 2004; Pfister, Heinemann, Kiesel, Thomaschke, & Janczyk, 2012). Free-choice and forced-choice actions are typically manipulated to probe these two systems, with free-choice actions mapping on the endogenous system and forced-choice actions mapping on the exogenous system (for criticisms of this dichotomy, see Khalighinejad, Schurger, Desantis, Zmigrod, & Haggard, 2018; Nachev & Hacker, 2014). Initial findings from a functional perspective appeared to support the anatomical distinction between two separable endogenous and exogenous systems (e.g., Herwig & Waszak, 2009; Herwig, Prinz, & Waszak, 2007; Waszak et al., 2005; see Pfister, 2019, for an alternative interpretation). In contrast, more recent findings suggested that these are not separate systems (e.g., Bermeitinger & Hackländer, 2018; Hommel & Wiers, 2017; Hughes, Schütz-Bosbach, & Waszak, 2011; Janczyk, Heinemann, & Pfister, 2012; Janczyk, Nolden, & Jolicoeur, 2015; Janczyk, Pfister, Wallmeier, & Kunde, 2014; Mattler & Palmer, 2012; see also Prinz, 1998, for a converging perspective). However, behavioral evidence supporting the same-system assumption comes from similarities in dual-task interference (Janczyk et al., 2014, 2015) and action-effect associations or bindings (Janczyk et al., 2012) between free-choice and forced-choice responses. To date, there is no clear-cut evidence to our knowledge that examines whether free-choice and forced-choice action plans actually share the same cognitive representations, which would unequivocally rule out the assumption of separate systems for endogenous and exogenous actions.

A particularly relevant set of findings supporting separable endogenous and exogenous systems has accumulated in so-called truncation experiments (Astor-Jack & Haggard, 2005; Obhi & Haggard, 2004; Obhi, Matkovich, & Gilbert, 2009). These studies compared forced-choice response times (RTs) to an interrupting tone while participants concurrently planned and maintained a free-choice action in memory to a situation in which they did not pre-plan an action. Critically, the forced-choice responses were identical to the pre-planned, free-choice response, so that participants simply were to perform the pre-planned response in case of an interrupting tone. Results showed slower RTs to the tone when a free-choice action was pre-planned compared when an action was not pre-planned. The observation of slower RTs to the tone while maintaining another action was attributed to the extra time needed to deactivate the endogenous system (maintaining the free-choice action) before the exogenous system (associated with tone) could trigger the action. This explanation is compatible with the idea that one and the same motor output can be controlled by two separate systems (endogenous and exogenous). An alternative interpretation of these findings, however, is that the slower responses to the tone while planning and retaining another action reflected the cost of feature code overlap between two competing action plans: the retained action plan and the action plan to the tone. This alternative perspective suggests that free-choice and forced-choice action plans operate on the same type of feature codes and hence are represented within the same cognitive domain. As such, free-choice and forced-choice actions would *not* be controlled by separate endogenous and exogenous systems.

No study, to our knowledge, has examined whether specific *feature codes* for free-choice and forced-choice action plans can compete or interfere with each other. Such interference would provide direct evidence that these two types of action plans share common codes and hence are represented within the same cognitive domain. Finding partial repetition costs for intervening free-choice responses would also indicate that the ability to execute internally generated action plans are influenced by future action goals retained in working memory – with a selection cost for internally generated actions that partly share feature codes with a future action goal.

Further, by utilizing a task that requires participants to retain a future action plan in working memory while concurrently executing a free-choice action to an intervening event, we can examine whether free-choice decisions can be biased by a future action plan (goal). We can also determine whether partial repetition costs, if observed, occur regardless of the presence or absence of free-choice decision biases. Research indicates that people tend to avoid choices that require more cognitive effort (Ballard, Hayhoe, & Pelz, 1995; Droll & Hayhoe, 2007; Dunn, Lutes, & Risko, 2016). Even for decisions that require few demands on cognition, the less cognitively effortful alternative is typically chosen (e.g., Fournier et al., 2019; Kool, McGuire, Rosen, & Botvinick, 2010) and may be more rewarding (Botvinick, Huffstetler, & McGuire, 2009; Botvinick & Rosen, 2009). Thus, if any response biases exist in selecting free-choice responses, we would expect to find a bias that circumvents partial feature overlap with the future action goal. Choosing an intervening action that does not partly overlap with the action plan retained in working memory could perhaps conserve cognitive effort that would otherwise be needed to resolve feature code competition or confusion (e.g., Behmer Jr & Fournier, 2014; Fournier, Behmer, & Stubblefield, 2014).

In addition, a bias to choose an intervening action that does *not* partly overlap with the future action plan retained in memory may serve to protect the future action plan from feature code competition or confusion. Consistent with this latter assumption, past research suggests that recalling a retained action plan is less accurate when it shares versus does not share an action feature with the intervening action – at least when both the retained and intervening actions require a forced-choice response (e.g., Fournier, Behmer, & Stubblefield, 2014; Mattson & Fournier, 2008; Fournier, Hansen, Stubblefield, & Van Dongen, 2018).

In sum, examining whether partial repetition costs occur for an intervening, free-choice action, while retaining a forced-choice action plan in working memory, we can determine the following. First, we can determine whether free-choice and forced-choice action plans share the same cognitive representations and hence are represented within the same cognitive domain, as opposed to separate endogenous and exogenous systems. Second, we can determine whether free-choice and forced-choice action plans share the same cognitive representations regardless of whether free-choice responses are biased or not. Third, we can determine whether any biases found for free-choice decisions would tend to reduce cognitive effort by avoiding feature code competition or confusion and preserve the retention of the future action goal in working memory.

The present study

We used the partial repetition paradigm by Fournier, Behmer, and Stubblefield (2014), which was originally conceptualized by Stoet and Hommel (1999). Participants viewed two different visual events (event A and event B) in a sequence. They planned and retained a forced-choice response (sequences of three successive key-press responses with the right or left hand) based on the identity of the first event (event A) while executing an immediate forced-choice or free-choice response (repetitive keypresses with the right or left hand) based on the identity of a second event (event B). Afterwards, the retained action to event A was recalled and executed. The action plans for the retained and intervening events required a sequence of different key-press responses that either required the *same* hand (e.g., "right" and "right"; actions partly overlap or partial repetition) or *different* hands (e.g., "left" and "right"; no action overlap or repetition).

If action plans representing free-choice and forced-choice decisions are similar, we should find a partial repetition cost for both types of responses when the intervening action and the retained action employ a different set of key-presses with the *same* hand (actions partly overlap; partial repetition) versus *different* hands (actions do not overlap; no repetition). Also, we should find a partial repetition cost for free-choice actions regardless of whether these actions are biased or not. If free-choice and forced-choice action plans do not share similar representations, we should find a partial repetition cost for forced-choice actions only.

In addition, if intervening, free-choice actions tend to be biased to conserve cognitive effort, we should find a preference in selecting a different hand (vs. the same hand) to that integrated with the action plan retained in working memory, to avoid partial action overlap (partial repetition). This bias may occur even though participants were instructed to equally weigh hand selection across trials when selecting free-choice responses. Finally, if a free-choice bias to avoid partial action overlap is observed and this bias preserves the future action goal retained in working memory, then recall of the retained action should be more accurate when there is no overlap versus partial overlap with the intervening, free-choice action.

Finally, to ensure participants retained an action plan in memory prior to executing the intervening action, we included trials in which no plan was made or retained in working memory during execution of the intervening action. We expected initiation of intervening actions to be longer for both free-choice and forced-choice responses while retaining (vs. not retaining) another action plan.

Method

Participants

Fifty-five undergraduate students from Washington State University (mean age 20.1 years, standard deviation 2.5, five left-handed, 38 female) participated for optional course credit in psychology classes. Effect sizes for partial repetition costs have been reported to be large in several 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, Behmer, & Stubblefield, 2014, 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 19 participants for a power of $1-\beta = .90$ when assuming that partial repetition costs come with a large effect size of $d_z = 0.80$ for free-choice actions as compared to the forced-choice actions used in previous research (with a two-tailed test at $\alpha = .05$, also targeting the pairwise comparison of overlap and no-overlap trials). We opted for a larger sample size, however, to be able to detect also smaller effect sizes ($1-\beta = .8$ for effect sizes of about $d_z = 0.4$) and to allow for meaningful analyses of choice biases (power analyses were performed with power.t.test function of R3.6.1). This study was approved by the Washington State University Institutional Review Board, and informed consent was obtained from all participants. Participants had at least 20/40 visual acuity as assessed by a Snellen chart.

Apparatus

All visual stimuli were presented in white Arial font on a black background on a 17-in. CRT monitor, approximately 51.5 cm in front of the participant. Responses were recorded using a custom response keypad (X-Keys XK80 USB Keyboard, Williamston, MI, USA), placed on a desk, centered at the participant's midline. Participants responded using three vertically aligned keys located at the bottom left and at the bottom right of the keypad. The horizontal separation between the left and right response keys (center-to-center) was 20 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 keypad 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 keypad were visible when looking down. E-Prime software (version 2.0.10.356; Psychology Software Tools, Inc., Sharpsburg, PA, USA) was used for stimulus generation, stimulus presentation, and data collection.

Stimuli and responses

Event A and action A (first event, retained action plan in working memory) Participants either planned and retained an action for event A (plan) or did not (no plan).

For *plan trials*, event A was an arrowhead (0.67° visual angle) pointing to the left or right and an asterisk (0.45° visual angle) located above or below the arrowhead. The arrowhead and asterisk (subtending 1.56° visual angle) were superimposed on the central fixation dot (0.17° visual angle). The arrowhead direction (left or right) indicated the response hand (left or right, respectively). The asterisk location (above or below the arrowhead) indicated the initial movement direction of the index finger relative to the center key on the keypad (upper key press, toward the CRT monitor, or lower key press, toward the participant's body, respectively). Thus, there were four different action plans: *left hand-move up* (left hand pressed center key, upper key, and center key again), *left hand-move down* (left hand pressed center key, lower key, and center key again), *right hand-move up* (right hand pressed center key, upper key, and center key again), and *right hand-move down* (right hand pressed center key, lower key, and center key again) mapped to the four different arrowhead-asterisk stimuli combinations.

For *no-plan trials*, event A was presented as two outward-pointing arrowheads (< >, 0.67° visual angle for each arrowhead, separated by 0.39° visual angle) located to the left and right of the fixation dot. For this stimulus, participants were instructed not to plan or retain any action for event A.

Event B and action B (intervening event, action plan executed immediately) Event B was one of three capitalized letters X, H or O (0.79° visual angle) superimposed on the fixation dot (shifted slightly below center of the dot, so that the dot was visible). The letters X and H were consistently mapped to a left or right response. Half the participants pressed the left center key twice with their left hand in response to the letter X and pressed the right center key twice with their right hand in response to the letter H; the other half had the opposite stimulus-response mapping. The letter O cued participants to choose among the two possible responses, and they were instructed to try to balance these choices across trials. Multiple key-presses were required for event B so that the action plans for event B and the action plans for event A represented two distinct sequences of keypresses (see Stoet & Hommel, 1999).

Procedure

At the beginning of the session, participants read instructions (self-paced) on the CRT monitor. Figure 1 shows the sequence of events within a trial. Each trial began with an initiation screen with a message that read "Press the center keys to continue." When the center keys were pressed with the right and left index fingers simultaneously, the trial started, and a fixation dot appeared for 1,250 ms. Next, event A appeared for 1,500 ms, followed by the fixation dot alone for 1,500 ms. During this time, participants either planned the action for event A (plan trials) or did not (no-plan trials). Then, event B appeared at the fixation dot for 100 ms and was followed by the fixation dot alone until action B was executed or 1,900 ms elapsed. Participants were instructed to execute action B as quickly and accurately as possible. Action B RT was recorded

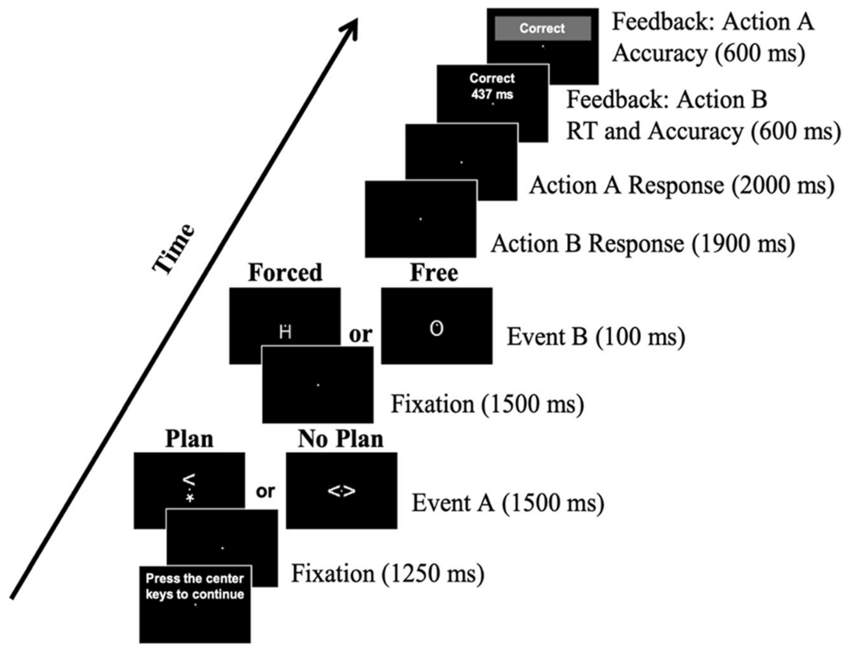


Fig. 1 Trial procedure. Participants first saw event A and either had to plan the corresponding action (action A) and retain this action plan in working memory (plan) or not (no plan). Then event B appeared – and before executing any planned action to event A, they performed either a forced-choice or free-choice action to event B (action B). When participants had to plan and retain action A in memory, action B could either partly overlap with action A (action-overlap present) or not overlap with action A (action-overlap absent)

as the time in milliseconds it took participants to make the first center key response after the onset of event B. After executing action B, participants either executed action A (plan trials) or did not (no-plan trials) during a 2,000-ms interval. Participants were instructed to execute action A as accurately as possible. After executing action A, or after the 2,000-ms interval elapsed, RT and accuracy feedback for action B was displayed for 600 ms followed by accuracy feedback for action A for 600 ms (if applicable). Following performance feedback, the initiation screen re-appeared, and participants initiated the next trial when ready.

Participants were instructed to not execute any part of action A until after executing action B and were not to move fingers or use external cues to help them remember action A – they were told to maintain action A in memory. For action B free-choice responses (i.e., to the letter O), participants were encouraged to avoid using any systematic response strategies while trying to balance choices of left- and right-hand responses to this stimulus.

Two factors were manipulated within participants: action overlap and response type. For action overlap, action B and action A either required the same hand (overlap present), different hands (overlap absent), or action A did not require a response and hence action overlap was not possible (no plan). For response type, action B either required a forced-choice response or a free-choice response among two response alternatives. Note that action B response errors for forced-choice actions could reflect an incorrect response or a failure to respond within the allotted response B time interval, while action B response errors for free-choice actions could only reflect a failure to respond within the allotted response B time interval.

Participants completed one 60-min session consisting of eight blocks of 48 trials with mandatory 10-s breaks at the end of each block. Within each block, the intervening event (event B) required forced-choice responses on 28 of the trials and free-choice responses on 20 of the trials. The 28 forced-choice trials contained 12 action-overlap-present trials, 12 action-overlap absent trials, and four trials in which no action was required for event A (no plan). Here, each event B stimulus (X, H) occurred with equal frequency and was paired equally often with all possible event A stimuli that did or did not require an action plan. In contrast, the 20 free-choice trials contained 16 trials with a variable number of action overlap-present and action overlap absent trials (dependent on participants' response choice) and four trials in which no action was required for event A (no plan). Here, the event B stimulus (O) was paired equally often with all possible event A stimuli that did or did not require an action plan. The 48 trials within each block occurred in a random order. The first block of trials was considered practice and was not analyzed. At the end of the experiment, participants completed a 10-question strategy survey.

Results

Participants who committed errors for action A on more than 80% of the trials (n=2), moved their hands in more than 50% of trials while planning the action A response (self-report;

n=4), or recently participated in a similar study in our lab (n=1) were not included in the final analyses. Of the original 55 participants who completed the study, 48 participants' data were analyzed.

Intervening (action B) free-choice and forced-choice actions

To evaluate partial repetition costs for the intervening actions, a 2 × 3 repeated-measures analysis of variance (ANOVA) with the factors of response type (forced choice vs. free choice) and action overlap (no plan, absent, or present) was performed on correct action B RTs. We then followed this up by conducting planned pairwise comparisons for free choice and forced choice trials separately. Also, a repeated-measures ANOVA with the factor of action overlap (no plan, absent, or present) was conducted on action B error rates for forced-choice responses, and a repeated-measures ANOVA with the factor of action plan (plan or no plan) was conducted on action B error rates for free-choice responses.[1] All three analyses were restricted to trials in which action A, if required, was accurate. All planned comparisons were conducted using a Tukey adjusted t-test with the "lsmeans" package in R (Lenth & Hervé, 2016) and Cohen's d_z calculated as $t/\sqrt{(n)}$ (Lakens, 2013).

Correct action B RTs Figure 2 shows the mean action B RTs as a function of response type and action overlap. There was a significant main effect of action overlap [$F(2,94)=29.91$, $p<.001$, $\eta^2=.39$] and a significant interaction [$F(2,94)=3.12$, $p=.049$, $\eta^2=.06$]; the main effect of response type was not significant ($F<1$). RTs were longer for action overlap-present versus -absent conditions for both forced-choice ($p<.001$) and free-choice ($p=.009$) responses indicating partial repetition costs for both response types. A partial repetition cost found for free-choice responses indicates that the intervening, free-choice action plan and the retained, forced-choice action plan contained feature codes that partly overlapped, and hence both action plans were represented within the same cognitive domain. Also, as expected, RTs were longer when an action plan (action A) was retained versus not retained (no plan) in working memory; RTs for action overlap-present and -absent trials were significantly longer than no-plan trials for both forced-choice ($p=.005$ and $p<.001$, respectively) and free-choice ($p=.002$ and $p<.001$, respectively) responses. This indicates that retaining an action plan in memory, regardless of action overlap, delayed responding to the intervening event; however, this conclusion may be compromised by a speed-accuracy tradeoff (discussed below). Finally, no significant difference in RTs between forced-choice and free-choice

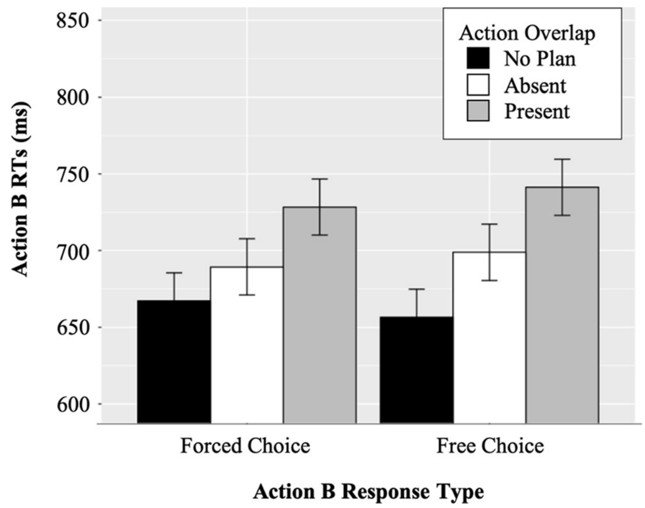


Fig. 2 Reaction times (RTs) for action B as a function of response type (forced choice vs. free choice) and action overlap (no plan, absent, and present). Error bars represent within-subject standard errors (Loftus & Masson, 1994)

responses occurred for any of the action overlap conditions ($p=.989$ for no plan, $p=.314$ for absent overlap, and $p=.166$ for present overlap). This suggests that the size of the partial repetition costs obtained did not differ for forced-choice and free-choice responses.

To evaluate the significant interaction above, the RT differences among the action overlap conditions were compared between the forced-choice and free-choice response types. The size of the RT difference between the action-overlap-present and -absent conditions was not significantly different between forced-choice ($M=39$ ms) and free-choice ($M=43$ ms) responses, $t(47)=0.49$, $p=.630$. Also, the size of the RT difference between no plan and action overlap absent was not significantly different between forced-choice ($M=22$ ms) and free-choice responses ($M=43$ ms), $t(47)=1.87$, $p=.067$. However, the size of the RT difference between no plan and action overlap present was significantly larger for free-choice ($M=86$ ms) than for forced-choice ($M=62$ ms) responses, $t(47)=2.35$, $p=.022$, $d=-0.339$. These latter findings suggest that retaining an action plan in memory may have delayed free-choice responses more than forced choice responses; however, as indicated below, this conclusion may be due to a speed-accuracy tradeoff.

Action B error rates for forced-choice responses There was a significant effect of action overlap [$F(2,94)=14.78$, $p<.001$, $\eta^2=.24$]. Planned comparisons showed that error rates for no plan ($M=6.98\%$) were greater than those for action overlap-present ($M=2.83\%$; $p<.001$) and action overlap-absent trials ($M=3.27\%$; $p<.001$); but there was no difference between action overlap-present and -absent trials ($p=.892$). The higher error rates found for the no-plan compared to trials in which an action plan was retained (action overlap-present and -absent

[1] Note that action overlap was not defined for free choice errors as these errors were only due to failures to respond within the action B time window of 2,000 ms.

trials) may be due to a speed-accuracy tradeoff because action B RTs were faster for the no-plan than for the action overlap-present and -absent trials (reported above). Thus, performance differences relative to the no-plan conditions should be interpreted with caution. Importantly, no speed-accuracy tradeoffs were found for forced-choice responses when comparing action overlap-present and -absent conditions.

Action B error rates for free-choice responses There was a significant effect of action plan [$F(1,47)=5.07$, $p=.029$, $\eta^2=.10$] indicating that error rates were significantly greater when *no* action plan was retained ($M=0.62\%$) compared to when an action plan was retained ($M=.12\%$) in working memory. Although the mean difference is small, it suggests that the shorter free-choice RTs found for the no planning conditions may be partly due to a speed-accuracy tradeoff. Thus, the conclusion that the no-plan condition was faster than the action-plan condition for free-choice responses should be interpreted with caution.

Free-choice response bias and partial repetition costs

We examined whether partial repetition costs found for free-choice responses occurred regardless of whether participants showed a bias in responding to the intervening event or not. To accomplish this, we evaluated performance in the free-choice conditions by comparing action B RTs for those participants who showed a bias in responding to action B compared to those who did not. We observed a bias based on action overlap, consistent with predictions, and a bias based on hand preference. These response biases are described separately below. Biases for free-choice responses were expected for most participants because such biases would reduce cognitive load while maintaining an additional action plan in memory.[2] Three different mixed-design ANOVAs with the within-subject factor of action overlap (absent, present) and the between-subject factor of group (biased, unbiased) were conducted on action B RTs to evaluate the effect of action-overlap bias and the effect of hand bias on partial repetition costs (see below for details on the coding of the factor group). All analyses were restricted to trials in which the retained action (action A) was accurately recalled.

Action overlap bias For free-choice trials, frequencies of action B responses for each participant were categorized by action overlap (absent or present). Figure 3 shows the number of participants who made overlap-absent responses at a particular frequency when event B signaled a free-choice response. Participants who executed an overlap-absent response 30% of the time or less (i.e., showed an overlap-present bias) or executed an overlap-absent response 70% of the time or more (i.e., showed an overlap absent bias) were assigned to the action-overlap biased group and all other participants were assigned to the action-overlap unbiased group. As a result, among the 48 participants, ten had an overlap-absent bias, and one had an overlap-present bias. Thus, 11 participants were assigned to the action-overlap biased group, and 37 participants were assigned to the action-overlap unbiased group.

The ANOVA for action B free-choice RTs showed a significant main effect of action overlap [$F(1,46)=44.89$, $p<.001$, $\eta^2=.49$] and a significant interaction between action overlap and group [$F(1,46)=5.95$, $p=.019$, $\eta^2=.11$]; the main effect of group was not significant [$F<1$]. As shown in Fig. 4, RTs for action-overlap-present responses ($M=744$ ms) were longer than overlap-absent responses ($M=701$ ms), indicating a partial repetition cost regardless of whether there was an action-overlap bias. Also, a Welch's two-sample *t*-test showed that the size of the partial repetition cost was larger for participants who showed an action-overlap bias ($M=73$ ms) compared to those who did not ($M=34$ ms); $t(18.33)=2.61$, $p=.017$, $d=2.645$. Importantly, a one-sample *t*-test also showed that partial repetition costs occurred for participants who did not show an action-overlap bias [$t(36)=4.34$, $p<.001$, $d = 0.626$], and hence partial repetition costs were not restricted to participants who showed a response bias related to action overlap.

Also, consistent with our predictions, the participants of the biased group were more likely to show an absent-overlap than an overlap-present bias ($n_{absent} = 10$ vs. $n_{present} = 1$). This observation was qualified by a chi-square test of independence, $\chi^2(1, n=11)=7.36$, $p=.007$. Furthermore, this conclusion held when using a more liberal measure of action-overlap bias (an absent-overlap bias of more than 50% vs. 50% or less). That is, our entire sample of participants were overall more likely to show an absent-overlap bias ($n_{absent >50\%} = 35$) than an overlap-present bias ($n_{absent \leq 50\%} = 13$), as qualified by a chi-square test of independence, $\chi^2(1, n=48)=10.08$, $p=.001$.

Hand bias For free-choice trials, frequencies of action B responses for each participant were categorized by the hand used to respond (right or left). Figure 5 shows the number of participants who responded with the right hand at a particular frequency when event B signaled a free-choice response. Participants who responded with the right hand 30% of the time or less (i.e., showed a left-hand bias) or responded with the right hand 70% of the time or more (i.e., showed a right-hand bias) were assigned to the biased group, and all other participants were assigned to the unbiased group. As a result, among the 48 participants, 37 were categorized as "no hand bias," and 11 participants were categorized as "hand bias" (11 right-hand bias, 0 left-hand bias).

[2] Visual inspection of the individual raw data did not reveal any biased strategies used between blocks related to choosing one hand and then switching to another or using the same hand required for action A and then switching to another.

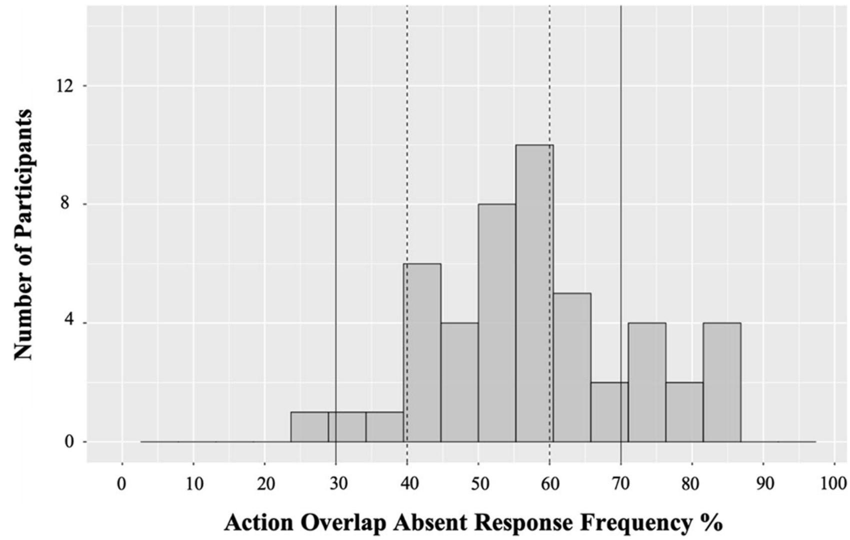


Fig. 3 The frequency of action-overlap absent responses for each participant (n=48). Participants within the solid vertical lines were assigned to the unbiased, action-overlap group and those falling outside the solid vertical lines (showing an action overlap bias of 70% or greater) were assigned to the biased, action-overlap group. Additionally, participants within the dashed lines were assigned to a more conservative, unbiased, action-overlap group (an action overlap bias less than 60%)

The ANOVA for action B free-choice RTs showed a significant main effect of action overlap [$F(1,46)=22.80$, $p<.001$, $\eta^2=.33$]; the main effect of group ($F<1$) and the interaction ($F<1$) were not significant. This indicates that action B responses were longer for action-overlap-present versus -absent trials, consistent with a partial repetition cost (see Fig. 6). Also, a partial repetition cost occurred regardless of whether there was a hand bias or not, and the size of the partial repetition cost did not differ based on hand bias. Importantly, these results again show that partial repetition costs were not restricted to participants who showed a response bias.

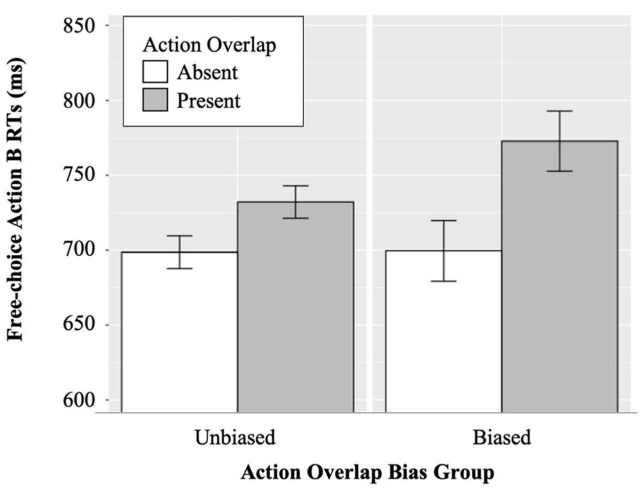


Fig. 4 Reaction times (RTs) for freely chosen action B responses for the 37 participants assigned to the unbiased, action-overlap group (unbiased group; action overlap bias less than 70%) and the 11 participants assigned to the biased, action-overlap group (biased group; action overlap bias equal to or greater than 70%) by action overlap (absent, present). Error bars represent within-subject standard errors (Loftus & Masson, 1994)

Also, a significant number of participants showed a hand bias. A chi-square test of independence showed that the number of individuals (11 of 48) who chose one hand (i.e., the right hand) more frequently than the other was significantly different than zero, $\chi^2(1, N=48)=14.08$, $p<.001$.

Action overlap and hand bias To further explore the effect of bias on partial repetition costs, participants who executed an absent action-overlap response at a frequency between 40% and 60% (see Fig. 3, dashed lines) and used their right hand at a frequency between 40% and 60% (see Fig. 5, dashed lines) were assigned to the unbiased group. All other participants were assigned to the biased group. Inclusion into the unbiased

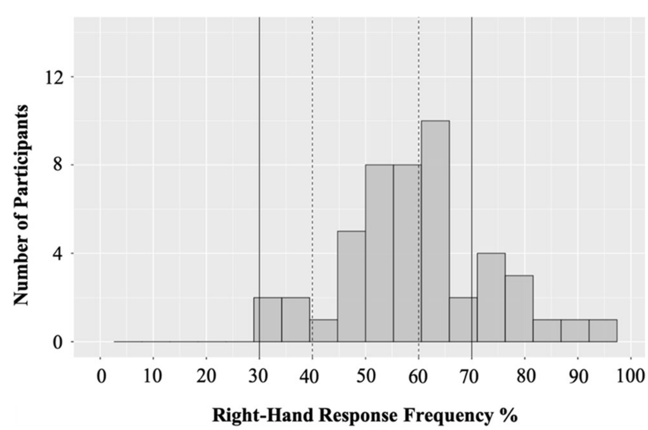


Fig. 5 The frequency of right-hand responses for each participant (n=48). Participants within the solid vertical lines were assigned to the unbiased-hand group and those falling outside the solid vertical lines (showing a hand bias equal to or greater than 70%) were assigned to the biased-hand group. Additionally, participants within the dashed lines were assigned to a more conservative, unbiased-hand group (a hand bias less than 60%)

group was more conservative here than in the analyses above because we wished to determine whether action overlap costs would continue to be observed using this more conservative criterion. As a result, among the 48 participants, 32 were assigned to the unbiased group and 16 were assigned to the biased group.

The ANOVA for action B RTs showed a significant main effect of action overlap [$F(1,46)=29.65$, $p<.001$, $\eta^2=.39$]; the main effect of group ($F<1$) and the interaction ($F<1$) were not significant. Again, a partial repetition cost was observed for both unbiased and biased participant groups, and the size of the partial repetition costs did not differ based on bias (see Fig. 7).

Scatterplots showing the size of the partial repetition cost by action-overlap bias and by hand bias for each participant are presented separately in the Appendix 1 and Appendix 2. These plots further demonstrate that partial repetition costs were not contingent on a response bias for free-choice responses.

Recall accuracy of the retained, action plan (action A)

To evaluate whether recall accuracy of the retained action plan (action A) was influenced by action overlap with the intervening action (action B), a 2 × 2 repeated-measures ANOVA with the factors of response type (forced choice vs. free choice) and action overlap (absent vs. present) was conducted on action A error rates[3]. The mean action A error rates by response type and action overlap are presented in Table 1. There was a main effect of action overlap [$F(1,47)=31.25$, $p<.001$, $\eta^2 = .40$] indicating that action A error rates were greater when action overlap was present ($M=11.41\%$) compared to absent ($M=6.34\%$). The main effect of response type [$F(1,47)=3.38$, $p=.072$, $\eta^2=.07$] and the interaction [$F(1,47)=.55$, $p=.463$, $\eta^2=.01$] were not significant. This suggests that a response-overlap cost occurred when recalling action A responses regardless of whether action B required a forced-choice or free-choice response. Supplementary analyses (see Appendix 3) also show response overlap costs for action B free-choice responses regardless of response biases.

Discussion

Retaining a forced-choice action plan in memory to one event delayed execution of both free-choice and forced-choice action plans to a second, intervening event when the retained and intervening action plans partly overlapped (i.e., required the same response hand but different keystrokes) versus did not overlap (i.e., required different response hands and keystrokes). This indicates that a partial repetition cost occurred for both intervening, forced-choice (exogenous), and free-choice (endogenous) actions while retaining a forced-choice (exogenous) action. Also, partial repetition costs were robust for intervening, free-choice responses as these costs occurred

[3] We did not analyze RT for action A for two reasons. First, we asked participants to take their time to respond to A in order to respond as accurately as possible and they were told that we were not concerned with how fast they responded, only how accurate they responded. Second, RT for action A was confounded with responses executed to action B. That is, when there was action overlap (i.e., actions A and B shared the same response hand), the motor response for action A had to wait for action B to finish before it could start, but when there was no action overlap, the motor response for action A did not necessarily have to wait for action B to finish before it could start.

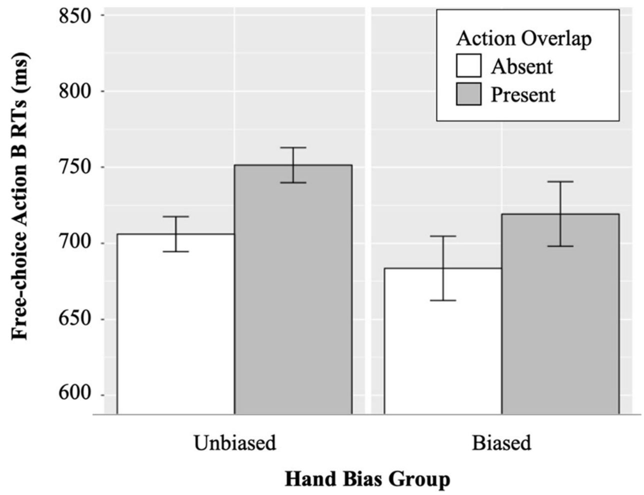


Fig. 6 Reaction times (RTs) for freely chosen action B responses for the 37 participants assigned to the unbiased-hand group (unbiased group; hand bias less than 70%) and the 11 participants assigned to the biased-hand group (biased group; hand bias equal to or greater than 70%) by action overlap (absent, present). Error bars represent within-subject standard errors (Loftus & Masson, 1994)

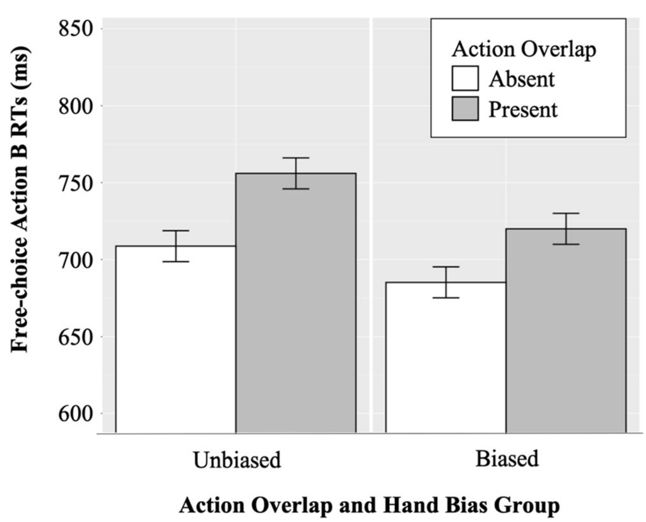


Fig. 7 Reaction times (RTs) for freely chosen action B responses for the 32 participants assigned to the unbiased group (hand and action overlap bias less than 60%) and the 16 participants assigned to the biased group (hand and/or action overlap bias equal to or greater than 60%) by action overlap (absent, present). Here, participant assignment to the unbiased group was based on the more conservative criterion shown in Figs. 3 and 5. Error bars represent within-subject standard errors (Loftus & Masson, 1994)

Table 1 Mean recall error rates and within-subject standard errors (SEs) for the retained action plan (action A) by response type and action overlap

Action overlap	Response type			
	Free choice		Forced choice	
	Mean %	SE %*	Mean %	SE %*
Absent	5.66	(0.80)	7.15	(0.80)
Present	11.16	(0.80)	12.02	(0.80)

*Loftus and Masson (1994)

regardless of whether participants did or did not show free-choice response biases (related to action overlap and/or a hand preference). These results show that the efficiency of executing a free-choice (endogenous) response, in addition to a forced-choice (exogenous) response, is influenced by a future action plan retained in working memory. Moreover, partial repetition costs found for free-choice responses suggests that the intervening, free-choice (endogenous) action plan and the retained, forced-choice (exogenous) action plan utilized similar cognitive representations, and hence they shared the same cognitive system (e.g., Bermeitinger & Hackländer, 2018; Hommel & Wiers, 2017; Janczyk et al., 2012; Janczyk et al., 2015; Janczyk et al., 2014; Khalighinejad et al., 2018). This interpretation is consistent with the assumption that partial repetition costs occur when the intervening and retained action plans are represented within the same cognitive domain and share common feature codes (Prinz, 1997). This interpretation is also consistent with the assumption that actions either compete for binding of relevant codes (Hommel et al., 2001; Stoet & Hommel, 1999) or compete for response selection due to common code confusion (Fournier, Gallimore, et al., 2014; Hommel, 2004, 2005; Mattson et al., 2012).

Our results further showed that a significant proportion of our participants were biased to freely choose intervening actions that did *not* partly overlap with the action plan retained in working memory. This suggests that participants tended to choose actions that would minimize cognitive effort by avoiding code competition or confusion. Also, because recall accuracy of the retained action was poorer for partial repetition trials, the bias to avoid intervening actions that partly overlapped with the action plan retained in working memory led to improved recall accuracy of the retained action. This suggests that free-choice responses may be additionally biased to preserve the retained, future action plan.

Partial repetition costs found for free-choice responses while retaining a future action plan based on a forced-choice response indicate that the action plans for these two types of responses are represented similarly. Importantly, partial repetition costs occurred regardless of whether participants showed a response bias related to action overlap or a bias in favor of one response hand. Thus, while it could be argued that free-choice response biases may reduce the number of voluntary response options, leading a free-choice response to resemble a forced-choice response, such response biases cannot account for the partial repetition costs observed. The robust partial repetition costs found for biased and unbiased free-choice responses indicate that free-choice and forced-choice responses are represented similarly regardless of response biases. This finding is important as it suggests that endogenous and exogenous actions may be more accurately depicted as actions that fall along a continuum within the same representational domain (Janczyk et al., 2015; Hommel & Wiers, 2017; Obhi et al., 2009; Pfister, Kiesel, & Hoffmann, 2011). That is, free-choice actions may more closely resemble forced-choice actions when biases or context influence free-choice decisions, and perhaps forced-choice actions more closely resemble free-choice actions when stimulus-response mappings are variable as opposed to consistent.

This conclusion is consistent with those drawn in other studies that showed dual-task costs for both free-choice and forced-choice response tasks (Janczyk et al., 2015) and in studies that showed a reliable impact of action-effect anticipationsfor free-choice and forced-choice responses alike (Gaschler & Nattkemper, 2012; Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014; Pfister & Kunde, 2013). However, as discussed previously, it contrasts with the conclusions from truncation studies (Astor-Jack & Haggard, 2005; Obhi & Haggard, 2004; Obhi et al., 2009) which posit separate endogenous and exogenous systems. For example, Obhi et al. (2009) found RT delays in executing an action triggered by a stimulus while maintaining a free-choice action (vs. not maintaining an action), even though the two actions implied identical motor output. These RT delays were assumed to be due to the extra time needed to deactivate the endogenous system before the exogenous system could activate the required movement.

However, the theory of event coding (Hommel et al., 2001; Hommel, 2004, 2005) and past research that has utilized the partial repetition task (e.g., Stoet & Hommel, 1999; Wiediger & Fournier, 2008; see also Müsseler & Hommel, 1997) would predict that the partial feature overlap between the retained, pre-planned action and the forced-choice action plan would lead to slower responding compared to when no pre-planned action was retained. That is, delays would be due to feature-code competition or confusion between the two action plans, which is consistent with the concept of one common representational domain. Thus, we suggest that the findings in these truncation studies provide evidence, consistent with ours, that internally generated, endogenous actions and externally triggered exogenous actions are represented similarly and hence are not represented or controlled by different action systems.

Our response tasks as well as those in the truncation experiments described above required actions that relied on stimulus identification and/or memory that can be generated "offline," associated with ventral stream processing (e.g., Milner & Goodale, 1995, 2008; Wiediger & Fournier, 2008). We did not utilize actions that only rely on the metrics of the stimulus to guide actions that are generated "online" (e.g., Glover, 1999; Glover et al., 2012), associated with dorsal stream processing (e.g., Goodale, 2016; Milner & Goodale, 1995, 2008). If the intervening actions could be generated "online" (relying on the dorsal stream), while retaining a future action plan in memory (which would rely on the ventral stream), we would not expect to find a partial repetition cost for either free-choice or forced-choice actions. Indeed, it has been previously shown that partial repetition costs occur for intervening actions that are generated offline, but do not occur for intervening actions that are generated online (Fournier et al., 2015; Wiediger & Fournier, 2008), indicating that these actions do not share the same representations or action systems (see also Glover, 1999; Glover et al., 2012; review by Thomaschke, Hopkins, & Miall, 2012), consistent with the two-system assumption of Milner and Goodale (1995, 2008).

Our study also provides evidence, consistent with previous decision-making research, that free-choice decisions are influenced by cognitive effort. A significant proportion of our participants freely chose intervening actions that did not overlap with the future action plan retained in working memory. This bias occurred even though participants were instructed to equally weight selection of right-hand and left-hand responses across trials when cued to select a free-choice response. This tendency suggests that participants were more likely to select responses that did not have features that were currently bound to another action plan (e.g., Hommel et al., 2001). Selection of actions that require features currently bound to another action plan is assumed to lead to code competition (e.g., Hommel et al., 2001; Stoet & Hommel, 1999) or code confusion (e.g., Fournier, Gallimore, et al., 2014; Hommel, 2004, 2005; Mattson et al., 2012), and overcoming code competition or code confusion is assumed to require more cognitive effort than simply choosing an action plan that does not have features currently bound to another action plan (e.g., Fournier et al., 2018). Thus, we suggest that our participants were biased to make free choices that minimized cognitive effort. This is consistent with research on decision making that shows that participants will tend to make choices, even choices that appear suboptimal, that conserve cognitive effort (Botvinick & Rosen, 2009; Botvinick et al., 2009; Dignath, Kiesel, & Eder, 2015; Fournier et al., 2019; Kool et al., 2010).

Moreover, people who showed greater partial repetition costs showed a greater choice bias to avoid such costs (see scatter plot in Appendix 1), $r(46) = .284$, $p = .049$. Perhaps individuals who showed greater partial repetition costs had a greater need to reduce them, and hence showed a greater choice bias to avoid such costs. Perhaps there are individual differences in the bias to avoid costs (due to code competition or confusion) that may be linked to working-memory capacity. Consistent with this conjecture, Fournier et al. (2014) found greater partial repetition costs for participants with lower versus higher working memory spans in a forced-choice response task. Also, an EEG study by Behmer and Fournier (Behmer Jr & Fournier, 2014) showed those with lower working memory spans had reduced mu- and beta-event-related power over the left motor cluster while maintaining an action plan in working memory compared to those with higher working-memory spans. This suggests that working-memory capacity may modulate neural efficiency over motor components when maintaining an action plan (Behmer Jr & Fournier, 2014).

Recall accuracy of the retained action plan was also hindered when the intervening action partly overlapped (vs. did not overlap) with the retained action plan irrespective of whether the intervening action was a free-choice or a forced-choice response. This suggests that selecting an action plan that did not have features bound to another action plan led to faster, and hence more efficient, execution of the intervening action as well as more accurate recall of the retained, future action plan. Thus, the free-choice bias toward selecting intervening actions that did not have features bound to the retained, future action plan may have been more rewarding due to overall, better task performance. Together, these findings suggest that a retained, future action plan in working memory can influence intervening, free-choice responses. These internally generated actions can be influenced by the context of the task and are likely to be biased toward efficiency – improving overall response performance and reducing cognitive effort.

However, there is another possible explanation for this free-choice bias. When the intervening and retained action partly overlapped, activation of the retained action could not be activated until the intervening response was completed because both actions required the same hand. By choosing an intervening action plan that did *not* overlap with the retained action plan, the action plan retained in memory could be activated before the response to the intervening action was completed because the two actions required different hands. Thus, the tendency to avoid feature overlap when choosing the intervening action may be more efficient and rewarding because one could complete execution of the retained action plan sooner to end the trial. This possibility appears unlikely, however, because participants who showed no free-choice response biases as well as participants who showed a free-choice hand preference showed similar benefits in performance when choosing an intervening action that did not overlap with the retained action plan. Similar benefits in performance were also found for forced-choice responses. This suggests that the physical limitations on the ability to initiate the retained action (action A) immediately were not likely responsible for the free-choice response biases observed, but were instead due to minimizing cognitive effort and additionally improving task performance outcomes (see Stoet & Hommel, 1999, who showed similar overlap costs using different limbs). We further suggest that those participants who showed a preference to choose one hand (i.e., dominant hand) over the other also did so likely to reduce the cognitive effort required to balance free-choice response options across trials.

In sum, although we showed that free-choice and forced-choice action plans are represented similarly, free-choice decisions often operate on more complicated rules that incorporate complex integrations of different types of information such as context, memory of past actions, emotions, and maintenance of response options compared to direct stimulus-response activations present in forced-choice decisions in which a stimulus is consistently mapped to a response (Gozli, 2019; Schüür & Haggard, 2011). We also provide evidence that free-choice responses are sensitive to cognitive load.

Conclusion

Our findings provide decisive evidence that endogenously and exogenously generated action plans are represented similarly and hence are not controlled by separate endogenous and exogenous systems. This speaks against dual-system theories of human action control that typically reserve distinct mechanisms and representations for these two types of actions. Moreover, human agents appear to leverage the processing characteristics of the cognitive system by adjusting their choice behavior to allow for maximally efficient and effortless action control.

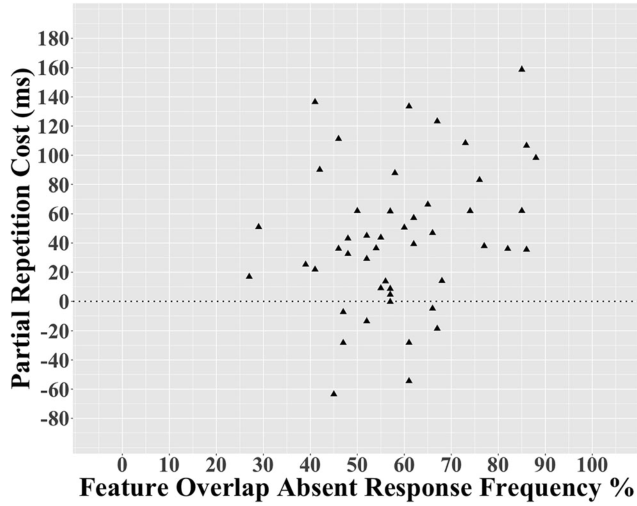
Compliance with ethical standards

The authors declare that they have no conflicts of interest. 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 Declaration of Helsinki and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

Open practices statement Open Practices Statement Data and analysis materials can be found at the following URL: https://research.libraries.wsu.edu/xmlui/handle/2376/16841. This study was not pre-registered.

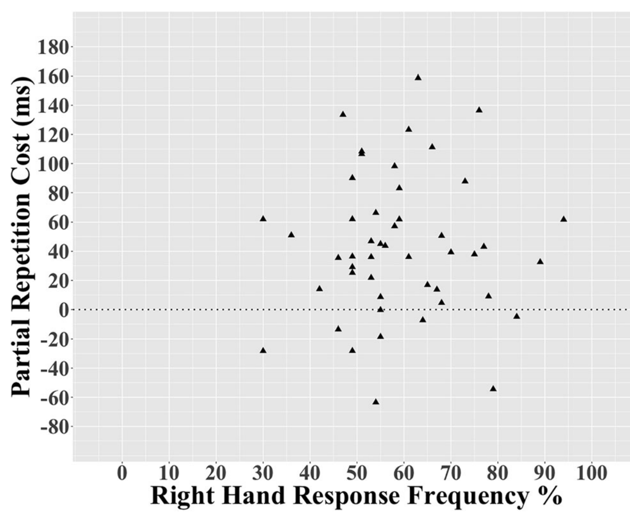
Appendix 1

Action-overlap-absent response frequency by partial repetition costs (values above 0) for free-choice responses for each individual participant (n=48). Data indicate that partial repetition costs for free-choice actions were not dependent on action overlap biases. Also, increases in partial repetition costs were positively associated with overlap-absent response frequency (i.e., avoidance of choosing partial overlapping action), $r(46) = .284$, $p = .049$.



Appendix 2

Right-hand response frequency by partial repetition costs (values above 0) for free-choice responses for each individual participant (n=48). Data indicate that partial repetition costs were not dependent on hand biases. Also, increases in partial repetition costs were not associated with right-hand response frequency, $r(46) = .025$, $p = .862$.



Appendix 3

Free-choice response bias and recall accuracy of the retained, action plan (action A)

We further evaluated performance in the free-choice conditions by comparing action A accuracy for those participants who showed a response bias to the intervening event compared to those who did not. Three separate 2 × 2 mixed-design ANOVAs with the factors of group (bias, no bias) and action overlap (absent, present) were conducted on action

A error rates for the action overlap bias, hand bias, and both action-overlap and hand-bias response group classifications for action B (reported in the results). The table below shows the mean action A error rates for each bias and action-overlap condition when action B required a free-choice response.

Mean recall error rates and within-subject standard errors (SEs) for the retained action plan (action A) by action overlap when the intervening action (action B) required a free-choice response. The error rate data for action A are presented separately for the different types of response biases observed for free-choice, action B responses (action overlap bias, hand bias, and both action overlap and hand bias, respectively)

Type of bias	Action overlap	Mean %	SE %*
Action-Overlap Bias	Absent	4.72	(3.80)
	Present	16.64	(3.80)
Hand Bias	Absent	4.81	(4.07)
	Present	12.18	(4.07)
Action-Overlap Bias and Hand Bias	Absent	6.47	(3.29)
	Present	12.76	(3.29)

*Loftus and Masson (1994)

All three analyses found a significant main effect of action overlap indicating that action A error rates were greater in the action-overlap-present condition regardless of whether there was a particular bias (action overlap, hand, or both action overlap and hand) or not [for action-overlap bias, $F(1,46)=25.96$, $p<.001$, $\eta^2=.36$; for hand bias, $F(1,46)=14.25$, $p<.001$, $\eta^2=.24$; and for both action overlap and hand bias, $F(1,46)=13.27$, $p<.001$, $\eta^2=.22$]. Additionally, the ANOVA conducted on action-overlap bias showed a significant interaction [$F(1,46)=7.47$, $p<.01$, $\eta^2=.14$], suggesting that the difference in error rates between action overlap-present and -absent responses was greater for the bias group ($M=11.91\%$) compared to the no-bias group ($M=3.95\%$) – although a Welch's two-sample t test indicated that the difference was not significant $t(12.20)=2.09$, $p=.059$, $d=1.760$. No other effects were significant. Taken together, these findings show that recall accuracy for the retained action plan was hindered when free-choice responses to the intervening event overlapped versus did not overlap with the retained action plan, regardless of whether free-choice responses were biased or not.

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