Preparing for simultaneous action and inaction – Temporal dynamics and target levels of

inhibitory control

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Abstract

When a single action is required along with the simultaneous inhibition another action, this typically results in frequent false-positive executions of the latter (inhibition failures). Absence of inhibitory demands in dual-action trials can render performance less error-prone (and sometimes faster) than in single-action trials. In the present study, we investigated the temporal dynamics of inhibitory control difficulties by varying preparation time (for simultaneous action execution and inhibition). In two experiments, participants responded to a single peripheral visual target either with an eye movement toward it (Single Saccade), with a spatially corresponding button press (Single Manual), or with both responses simultaneously (Dual Action) as indicated by a color cue. Preparation time was manipulated via the cue-stimulus interval (CSI) within blocks (Experiment 1) and between blocks (Experiment 2). Overall, responses were faster with longer (vs. shorter) preparation time. Crucially, however, our results reveal the exact dynamics of how inhibition failures (and thus dual-action benefits) in both response modalities substantially decrease with longer preparation, even though the cue did not contain information regarding the fully specified response that needed to be inhibited (i.e., its direction). These results highlight the role of sufficient preparation time not only for efficient action execution but also for concurrent inhibitory performance. The study contradicts the idea that inhibition can only be exerted globally or on the level of a fully specified response. Instead, it may also be directed at effector system representations or all associated responses, suggesting a highly flexible targeting of inhibitory control in cognition.

Statements and Declarations

Word count: 10065

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inhibitory control

Recent research has demonstrated that the requirement to execute one action while

simultaneously inhibiting another, highly prepotent, action can sometimes be even more difficult

than executing two actions concurrently, that is, a relative dual-action performance benefit (e.g.,

Huestegge & Koch, 2014; Kürten et al., 2022; Raettig & Huestegge, 2018, 2021). In the present

study, we examined the temporal dynamics of such dual-action benefits by systematically

manipulating preparation time for simultaneous executive and inhibitory control demands. In two

experiments, a cue-stimulus interval (CSI) was varied on a trial-by-trial basis within blocks

(Experiment 1) or between blocks (Experiment 2). The results are informative regarding the

mechanisms underlying preparation for action inhibition in the context of simultaneous action

execution, and they highlight the flexibility in targeting inhibitory control in general.

Dual-action benefits as the result of differential inhibitory demands

Inhibitory processes as a hallmark of cognitive control (e.g., Miyake et al., 2000; Tiego et

al., 2018) have been studied extensively in the past, most prominently using the stop-signal

paradigm (Logan, 1994; Logan & Cowan, 1984; Matzke et al., 2018). In this paradigm, a

response is made to a *go* stimulus in most trials that is in some trials followed by a second *stop*

stimulus (after a variable time delay) requiring the cancellation of the previously specified

response. Participants thus usually either execute or inhibit (one specific) action in each trial. In

contrast, investigations of inhibitory control in the face of *concurrent* action execution – and how

this may lead to a benefit for dual- (vs. single-) action execution – are still scarce. Studies

employing the well-established Psychological Refractory Period (PRP) paradigm (Welford, 1952; see Pashler, 1994 for a review) have shown that an inhibitory (vs. executive) requirement in the second of two temporally overlapping tasks can slow down reactions in the first task (the so-called no-go backward crosstalk effect, e.g., Janczyk & Huestegge, 2017; Miller, 2006; Röttger & Haider, 2017). Note that similar to the stop-signal paradigm, this setup involves a stimulus that explicitly signals response inhibition (i.e., a no-go stimulus) in no-go trials. In a more naturalistic setting, it has been demonstrated that mental arithmetic performance is reduced in conditions in which all action has to be suppressed (e.g., by staying stock-still) compared with conditions in which concurrent movement is allowed (Langhanns & Müller, 2018). Although this latter study did not encompass two overt motor actions but rather action inhibition (vs. execution) and a cognitive task, it nevertheless illustrates the potential performance cost exerted by concurrent inhibitory demands.

Studies using variations of the Single-Dual Switch (SDS) paradigm (e.g., Kürten et al., 2022; Raettig & Huestegge, 2018, 2021; see also Huestegge & Strobach, 2021; Strobach & Huestegge, 2021) have taken a straightforward approach towards investigating simultaneous inhibitory and executive action control and ensuing dual-action benefits in a basic setting. The SDS paradigm combines the methodologies of the dual-task paradigm (e.g., Hirsch et al., 2018; Pelzer et al., 2022; Schacherer & Hazeltine, 2021) and the cue-based task-switching paradigm (e.g., Meiran, 1996; Sudevan & Taylor, 1987; for a review of both approaches see Koch et al., 2018). Participants frequently switched between responding to a stimulus (or stimuli) with either one single action (A), another, prepotent, single action (B), or a dual action (A + B), as indicated by a cue. This procedure required constant activation of all potentially relevant action representations in working memory in contrast to using pure single-task and dual-task blocks (Lussier et al., 2012; Schumacher et al., 2001). Note that this paradigm does not involve any

stimulus explicitly calling for inhibitory demands, as the cue simply signals which type of action is (not) required. The typical finding is a high frequency of false-positive executions (i.e., inhibition failures) of the prepotent action (B) in trials requiring only a single action (A) while errors of any kind (i.e., response omissions and responses toward the wrong direction) are very infrequent in dual-action trials (A + B). The dual-action benefit apparently resulted from a greater ease (as indicated by higher overall accuracy at the trial level) of dual-action (vs. single-action) execution. Such dual-action benefits were obtained when combining manual and (prepotent) saccade actions (Huestegge & Koch, 2014; Kürten et al., 2022) as well as vocal and (prepotent) manual actions (Raettig & Huestegge, 2018, 2021), the latter studies even demonstrating faster (i.e., not only less error-prone) dual-action (vs. single-action) execution.

In fact, the same pattern of results should be observable for any combination of effector systems based on a framework of cross-modal action control that assumes a mapping selection stage (instead of an a-modal response selection process for each individual response) in between perceptual processing and action execution (Huestegge & Koch, 2010). The term "mapping selection" refers to the binding of task-relevant mental representations (codes) currently active in working memory (Oberauer, 2005). For example, when combining manual and saccade actions, complete action specification would at least require binding one or two relevant modality codes (e.g., "saccade" and/or "manual") as indicated by the cue identity to a correct spatial code (e.g., "left" or "right") as indicated by the target stimulus. For example, in a dual-action trial with the stimulus appearing on the left side, both modality codes would need to be activated and bound to the "left" spatial code. In a corresponding single-action (e.g., Single Manual) trial, only the manual modality code would need to be bound to the "left" spatial code. Activation spreading to the somewhat prepotent "saccade" code, however, could lead to its erroneous binding into the action program, leading to a false-positive (saccade) execution. To prevent this unwarranted co-

activation of the wrong modality code from occurring, some form of inhibitory control needs to be enacted. The same basic mechanism could, in principle, lead to false-positive manual errors in single-saccade trials as well. Frequency of false-positive errors in any modality should depend on the pre-activation (or prepotency) of the respective modality code which should generally be higher in saccades triggered by sudden peripheral events compared to manual responses. In addition to such an inherent prepotency, the "urge" to (falsely) execute an action (type) in a particular trial should be increased (reduced) to the extent that execution (inhibition) of that action type was required in the previous trial (i.e., transient action prepotency, Kürten et al., 2022). The aim of the current study is to investigate the temporal dynamics of concurrent inhibitory and executive control, more specifically, the effect of preparation on the frequency of inhibitory failures in single-action trials.

Preparation for execution and inhibition

Beneficial effects of preparation are firmly established in the experimental psychological literature. In the most basic sense, providing an unspecific warning signal (i.e, without any prior information regarding the exact response demands) usually results in improved performance (e.g., faster RTs) compared to having no warning whatsoever due to an increased readiness to process stimuli and/or to produce speeded responses (Los et al., 2021; Steinborn et al., 2009, 2010; see Niemi & Näätänen, 1981 for a review of unspecific temporal preparation). Such unspecific temporal preparation, however, is unlikely to have a major impact in the SDS paradigm given that more task-specific preparation is called for by the cue indicating response type (but not response direction). In fact, simply raising unspecific action readiness could even be detrimental here when inhibition (in addition to execution) of an action is required. To avoid inhibition failures in an unrequired action modality without compromising the required action,

more specific and nuanced preparatory strategies are needed. Studies of motor preparation have demonstrated the benefit of partial cueing (Adam et al., 2000, 2008; Huestegge & Adam, 2011; Rosenbaum, 1980, see Rosenbaum, 1983 for a review). For example, cuing the required arm (left vs. right) prior to the target stimulus upon which only direction (left vs. right) of the movement has to be specified has resulted in better performance compared with a situation in which both arm and direction of movement have to be specified following the target (Rosenbaum, 1980). This shares obvious similarities with the present SDS scenario where the cue provides partial information about which action type is (not) required and which action direction is specified by the target stimulus. However, typical motor precuing studies only focused on preparation of to-be-executed components of an action while here the cue additionally indicates which type of action needs to be inhibited.

Utilization of (partly) informative cues is also a hallmark in the literature on cued task switching. Here, the cue signals upcoming task demands (and thereby a repetition or switch of tasks), without providing the complete information needed to execute the required responses. An increase of the temporal interval between cue and imperative stimulus (cue-stimulus interval, CSI) usually results in better performance overall (Meiran, 1996; Meiran et al., 2000), and in particular for task switches (vs. repetitions, see Kiesel et al., 2010 for a review). One typical explanation is that during the CSI, participants engage in a process of advance *task-set reconfiguration,* which can entail both the activation of currently relevant and the inhibition of currently irrelevant task representations (Koch et al., 2004, 2010). Transferring these ideas to the present SDS paradigm, it seems reasonable to assume that participants might indeed be able to simultaneously prepare for inhibitory demands even in the context of demands to execute another action. However, the notion of task-set reconfiguration is clearly not specific enough to provide

precise predictions regarding empirical outcomes in our present setup, and further elaboration of

the preparatory mechanisms, especially with regard to inhibitory control, is therefore desirable.

Studies employing the stop-signal paradigm (Logan, 1994; Matzke et al., 2018) usually

focused on *reactive* inhibition, that is the cancellation of a fully specified and potentially already

initiated response. In the current setting, this would only be possible after the target stimulus is

presented and should not result in an effect of preparation time on the frequency of inhibition

failures. However, more *proactive* inhibitory mechanisms have been demonstrated in some stop-

signal studies, in which a cue signals an upcoming inhibitory demand (Aron, 2011). Especially,

selective (vs. global) inhibition performance has been shown to improve by allowing for

preparation (Muralidharan et al., 2019). This approach shares similarities with the SDS paradigm

where inhibitory control can also be enacted proactively based on the cue signaling warranted

and unwarranted response types. There remain, nevertheless, important differences between the

(proactive and selective) stop-signal paradigm and the present SDS paradigm. First, even in

proactive stop-signal studies with preparation for inhibitory control, a specific *stop* signal

(distinct from the *go* stimulus) is typically used (e.g., Aron, 2011; Elchlepp et al., 2016). In the

present study, in contrast, there is only a single target stimulus defining the execution of the

warranted response(s). Second, even in selective proactive stop-signal studies usually only one

effector system (i.e., manual) is used which often leads to more global inhibition interference

effects (e.g., inhibition of a left-hand response slowing down execution of a right-hand response,

Muralidharan et al., 2019). Here, cross-modal (oculomotor *and* manual) action control (inhibitory

and/or executive) is required in every trial. A *global motor inhibition* preparatory strategy in

single-action trials would entail the timing of an initially non-selective reactive stopping of both

(required and nonrequired) modalities followed by the selective restart of the required action

(e.g., Bissett & Logan, 2014) or the pausing of all motor activity followed by the selective

cancellation of the unrequired action (e.g., Diesburg & Wessel, 2021). This would lead to reduced inhibition failures at the cost of prolonged or even omitted actions for the action modality that actually requires execution. A proactive, *flexibly-targeted inhibition* of only responses made with one effector system would instead enable the inhibition of the unwarranted action modality without affecting (or even allowing for executive preparation of) the required action modality.

The present study

Based on the considerations presented above, we conclude that neither global inhibition nor the inhibition of only one fully specified response are suited to promote preparatory improvements of performance in the present paradigm, which in the crucial trials of interest requires inhibition of one action while concurrently executing another. Therefore, the aim of the present study was to systematically investigate the temporal dynamics of executive and inhibitory mechanisms that give rise to dual-action performance benefits, specifically, the effect of preparation time on the frequency of inhibition failures (false-positive errors in single-action trials). Conditional on a prior cue, participants responded to a single peripheral visual target (cf., Fagot & Pashler, 1992) either with a spatially compatible manual button press only (which should require the inhibition of a prepotent saccade to this target), with a saccade to the target only (which should, to a lesser extent, require the inhibition of the spatially compatible button press), or with both actions together (which should require no inhibition at all). Preparation time was manipulated by varying the temporal interval between cue and target onset (CSI). In most contemporary cue-based task-switching studies, the CSI is manipulated in a trial-by-trial manner within blocks as this represents a more economic variant when compared with a block-wise manipulation (Meiran, 1996; Meiran et al., 2000). Therefore, in Experiment 1, we varied CSI

duration in a trial-by-trial fashion. However, it is important to consider that an intermixed implementation within blocks not only gives rise to sequential effects that could complicate interpretation but might even change the way participants represent the task in the first place (Los, 1996, 1999). We therefore conducted Experiment 2 with a block-wise CSI manipulation to generalize the results of Experiment 1. Four cue-stimulus intervals were chosen: 100 ms, 400 ms, 700 ms, and 1500 ms. This range is representative of typical task-switching and temporal preparation studies (Kiesel et al., 2010) and enabled us to study the effects of preparation time on both executive and inhibitory control processes in a sufficiently fine-grained manner.

The predictions are straight-forward. In line with previous research on task-set reconfiguration in the context of switching task demands, we expected, overall, decreasing RTs with increasing CSI. Participants should be able to activate the currently relevant responses in advance to speed up reactions. The effects of preparation time on trial-level accuracy and in particular on false-positives in saccades and manual responses, however, are especially informative regarding the temporal dynamics of inhibitory control failures underlying the occurrence of dual-action benefits. If participants prepare via a domain-general inhibition process (as predicted by a *global motor inhibition account*), any reduction of false-positive responses should come at the cost of false-negative errors (or strongly prolonged RTs) in the to-be-executed action modality. If inhibitory control can solely be reactively targeted at fully specified action patterns (e.g., a saccade to the left) as predicted by a *specified action inhibition account*, we would not expect the frequency of false-positive action executions to be affected by the manipulation of CSI duration since the cue only provided information about the action modality (or modalities) that need to be executed (or inhibited), not about the fully specified response. If, however, participants actively prepared not only for executive control demands by activating the appropriate action (modality) representations but also for inhibitory control demands (e.g., by

reducing the activation of inappropriate action type or effector system representations), as predicted by a *flexibly-targeted inhibition account*, we would expect to find decreasing rates of false-positive errors in either action modality as preparation time increases without strong detrimental (but rather beneficial) effects on the required responses in each trial.

With regard to the different modes of CSI manipulation (trial-by-trial in Experiment 1, block-wise in Experiment 2) we would not expect to find qualitatively different patterns in results if participants employed the same basic preparatory strategies. Quantitative differences, however, are conceivable given worse predictability and the potential for sequential effects of preparatory intervals (e.g., Los & Van Den Heuvel, 2001).

In an exploratory analysis, we will additionally compare error RTs of false-positive responses (i.e., inhibition failures) with correct RTs. This can be informative with respect to the nature of the errors and the inhibitory processes at play. Fast false-positive errors (relative to correct responses) would indicate that these inhibition failures represent quasi-reflexive actions that escaped a slower independently operating inhibition process, in accord with a classic independent race model of inhibitory control (Logan & Cowan, 1984; Matzke et al., 2018). Slow errors (relative to correct responses), in contrast, would be incompatible with an independent race between a "go" process and a "stop/inhibit" process. Slow inhibition failures could rather be the result of a demanding (but sometimes unsuccessful) attempt to resolve confusion between competing response types suggesting some degree of dependence of execution and inhibition (across response modalities).

Experiment 1

In Experiment 1, CSI duration was manipulated in a trial-by-trial manner. This method is comparable to the way preparation time is manipulated in typical task-switching studies (e.g., Hoffmann et al., 2003; Meiran, 1996; Meiran et al., 2000).

Method

Participants

Fourty-eight (79% female, 92% right-handed) volunteers (mean age = 23.50 years, SD = 3.04) participated in Experiment 1 in exchange for monetary compensation. All gave informed consent and had normal or corrected-to-normal vision without color blindness. Sample sizes for both experiments was determined from a previous study showing inhibition-based dual-action benefits (Kürten et al., 2022). We based the computation on the main effect of Response Demand on manual error rates ($\eta_p^2 = .06$) to be able to reveal any potential dual-action benefits in this (less prepotent) modality as well. Thirty-five participants would have been needed to achieve a power $1-\beta = .90$ at $\alpha = .05$. In accord with preregistered criteria, data sets of two participants were excluded due to an insufficient number of valid trials (< 10) in at least one of the experimental conditions. These data sets were later recollected with the help of new participants to ensure full counterbalancing. Data collection went from 10-21-2021 to 01-24-2022.

Apparatus and Stimuli

Participants were seated in front of a 21-inch CRT screen with a spatial resolution of 1024 x 768 pixels and a temporal resolution of 100 Hz at a viewing distance of approximately 67 cm. A chinrest with forehead support was used to minimize head movements during the experiment.

Saccade latencies and landing positions of the right eye were recorded using a desktop-mounted

Eyelink 1000 eye tracking system (SR Research, Mississauga, Ontario, Canada) with a sampling

rate of 1000 Hz. Manual responses were recorded using a Cedrus RB-840 response pad (Cedrus

corporation). A plus sign (size = 0.35°VA) served as the fixation cross at the screen center.

Initially presented in white, it would eventually change its color to either red, green, or blue,

thereby indicating response demands (see below). A white square (size = 0.35°VA x 035°VA)

served as the imperative stimulus and was presented at an eccentricity of 8°VA either to the left

or to the right of the screen center. The experiment was programmed using Experiment Builder

software (version 2.1.140, SR Research).

Procedure

At the beginning of the experimental session the participant received written and verbal

task instructions with speed and accuracy emphasized equally for each response alternative. Each

trial began with the presentation of a white fixation cross at the screen center. After 2000 ms the

fixation cross changed color to either red, green, or blue, serving as a cue to indicate response

demands (e.g., red: Single Saccade, green: Single Manual, blue: Dual Action). Each cue color

appeared with equal probability in each block thus rendering execution of both action types (in

single-action and dual-action trials) prepotent over inhibition of either action types (in single-

action trials only). The mapping of color to response demand was counterbalanced across

participants. After a variable cue-stimulus interval (CSI) of either 100 ms, 400 ms, 700 ms or

1500 ms duration, the imperative stimulus appeared either to the left or to the right of the screen

center. The imperative stimulus remained on screen for 1500 ms. Then, error feedback was

provided if no response was recorded within that time interval. No further error feedback (e.g.,

for incorrect responses or of error type) was given. Trials were separated by a blank-screen inter-

trial interval (ITI) of 500 ms. Participants first completed a short practice block of 24 trials (6 of

each CSI duration) that was excluded from further analyses. Then, participants completed ten

blocks of 72 trials each with a short break between blocks. At the beginning of each new block,

the eye-tracker was recalibrated. The experiment comprised 720 trials in total (60 per condition,

30 per condition and direction).

Design

The main dependent variable of the current study was error rate (%) as a measure of trial-

level accuracy. Errors included directional errors (i.e., left instead of right saccade/button press),

false-negative errors (e.g., omissions of saccades in single-saccade or dual-action trials) and, of

most theoretical interest, false-positive errors (saccades executed in single-manual trials, button

presses executed in single-saccade trials).[1] Note that since in each trial, errors in both response

modalities could be made, saccade and manual error rates were analyzed in two separate repeated

measures ANOVAs with Response Demand (Single Manual, Single Saccade, Dual-Action) and

CSI (100 ms, 400 ms, 700 ms, 1500 ms) as within-subject factors. Correct RTs were analyzed

accordingly, however since no error RTs were included in these analyses, the factor Response

Demand only comprised two levels in each modality (Single, Dual). All statistical analyses were

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[1] To allow for maximum comparability with previous studies on dual-action performance

benefits, errors of any kind were analyzed as a function of trial type (Single Manual, Single

Saccade, Dual-Action). Effects of preparation on errors as a function of error type can be

obtained from Figure S1 and Table S1 in the supplemental material.

performed using a significance level of α = .05. In cases of within-subject factors with three or more levels, a Greenhouse-Geisser correction was routinely applied.

Transparency and openness

This was a preregistered study. We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. Preregistrations as well as raw data and analysis scripts are available at: https://osf.io/rhy9v/

Results and Discussion

Data Treatment

Responses executed faster than 50 ms after stimulus onset (0.09% of all trials) were regarded as premature and excluded from all analyses. All remaining trials were analyzed for errors. From subsequent correct RT analyses, trials containing any type of response error (11% of all trials), as well as RTs deviating more than ±3 standard deviations (SDs) from the individual cell mean (0.14% of all trials) were excluded.

Error Data

 Figure 1

Error Rates (%) of Experiment 1

Note. Error Rates (%) in the oculomotor and manual modalities as a function of Response

Demand (Single Manual, Single Saccade, Dual) and CSI (100 ms, 400 ms, 700 ms, 1500 ms).

CSI was varied within blocks in a trial-by-trial manner. Error bars represent the 95% CI_{within}

following Cousineau-Morey corrections (O'Brien & Cousineau, 2014).
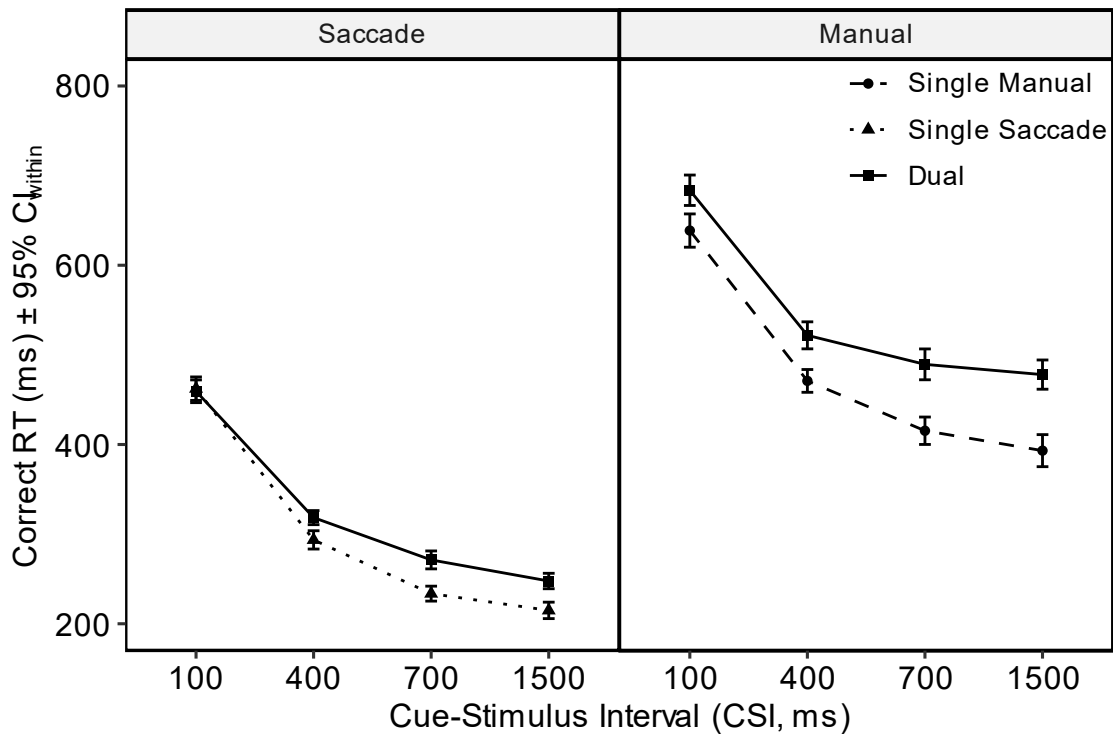
Figure 1 depicts error rates as a measure of trial-level performance separately for saccades

and manual responses as a function of Response Demand and CSI. Note that in the current study,

error rates comprised three types of errors: Directional errors (i.e., a saccade or button press in the

wrong direction), false-negative errors (i.e., not making a saccade or button press when required)

and false-positive errors (i.e., making a saccade or button press when not required). Saccade

(manual) errors in Single Manual (Single Saccade) trials therefore represent false-positive errors.

Descriptive summary statistics can be obtained from Table 1.

Saccade Errors. We found a significant main effect of Response Demand

$(F(1.03,48.33) = 56.11, p < .001, \hat{\eta}_p^2 = .544)$, indicating an overall dual-action performance

benefit for saccade accuracy. Saccade errors were, overall, more frequent in Single Manual trials

(15.69 %) than in Single Saccade trials (3.60 %) and Dual-Action trials (3.67 %, both ps < .001,

both $\hat{d}_z s > 1.084$). Saccade error rates did not differ significantly in Single Saccade and Dual-

Action trials ($p > .999$, $\hat{d}_z = -0.330$). The main effect of CSI was significant as well

$(F(2.00,94.23) = 91.63, p < .001, \hat{\eta}_p^2 = .661)$ indicating an improvement in overall saccade

accuracy with increasing preparation time. Critically, however, we observed a significant

interaction of Response Demand and CSI $(F(2.23,104.74) = 92.81, p < .001, \hat{\eta}_p^2 = .664)$.

Simple main effect analyses revealed that the effect of CSI was significant in Single Manual trials

$(F(3,47) = 53.05, p < .001, \hat{\eta}_p^2 = .772)$ and in Dual-Action trials $(F(3,47) = 3.46, p = .023,$

$\hat{\eta}_p^2 = .016)$, but not in Single Saccade trials $(F(3,47) = 1.27, p = .295, \hat{\eta}_p^2 < .001)$. Visual

inspection of Figure 1 indicates that with increasing preparation time, especially false-positive

saccade error rates in Single Manual trials became less frequent, while there was a slight increase

in saccade errors in Dual-Action trials (from 3.69 % at the 100 ms CSI to 4.25 % at the 1500 ms

CSI). The reduction in dual-action benefits with increasing preparation time was thus mainly

driven by the reduction in false-positive saccades. Bonferroni-adjusted post-hoc comparisons of

saccade error rates in Single Manual and Dual-Action trials revealed significant dual-action

benefits for all but the longest CSI durations (ps < .001, $\hat{d}_z s > 0.591$), however gradually

decreasing numerically from 25.77 percentage points at the shortest CSI (100 ms) to 6.17

percentage points at the second-longest CSI (700 ms). At the longest CSI, dual-action benefits were no longer significant (dual-action benefits of 3.98 percentage points, $p = .066$, $\hat{d}_z = 0.346$).

Manual Errors. The main effect of Response Demand was significant ($F(1.54,72.28) = 6.62$, $p = .005$, $\hat{\eta}_p^2 = .123$), indicating dual-action performance benefits. Overall, (manual) false-positive errors in Single Saccade trials (1.94 %) were more frequent than errors of any kind in Dual-Action trials (0.93 %, $p = .008$, $\hat{d}_z = 0.465$) Interestingly, we also found dual-action benefits caused by more frequent false-negative and/or false-direction manual button presses in Single Manual trials (2.23) compared with Dual-Action trials ($p = .001$, $\hat{d}_z = 0.586$). The main effect of CSI was significant as well ($F(2.12,99.61) = 13.93$, $p < .001$, $\hat{\eta}_p^2 = .229$). Overall, manual error rates decreased with increasing CSI duration (see Table 1). Crucially, we again found a significant interaction of Response Demand and CSI ($F(3.42,160.73) = 4.99$, $p = .002$, $\hat{\eta}_p^2 = .096$). Simple main effect analyses revealed a significant effect of CSI in Single Manual trials ($F(3,47) = 10.55$, $p < .001$, $\hat{\eta}_p^2 = .402$) and in Single Saccade trials ($F(3,47) = 8.28$, $p < .001$, $\hat{\eta}_p^2 = .346$) but not in Dual-Action trials ($F(3,47) = 0.74$, $p = .533$, $\hat{\eta}_p^2 = .045$), again indicating reduced dual-action benefits with increasing preparation time. Bonferroni-adjusted post-hoc comparisons of manual error rates in Single Saccade trials and Dual-Action trials revealed that false-positive-based dual-action benefits were significant at CSIs of 100 ms and 400 ms duration (both ps $< .004$, both $\hat{d}_z$s > 0.503) but not at CSIs of 700 ms and 1500 ms duration (both ps $> .404$, both $\hat{d}_z$s < 0.222).

RT data

Figure 2

Correct RTs of Experiment 1

Note. Mean correct RTs (ms) in the oculomotor and manual modalities as a function of Response Demand (Single Manual, Single Saccade, Dual) and CSI (100 ms, 400 ms, 700 ms, 1500 ms). CSI was varied within blocks in a trial-by-trial manner. Error bars represent the 95% CI_{within} following Cousineau-Morey corrections.

Figure 2 displays mean correct RTs in both modalities as a function of Response Demand (Single Saccade/ Single Manual, Dual) and CSI (100 ms, 400 ms, 700 ms, 1500 ms). Descriptive summary statistics are referred to in Table 1.

Saccade RTs. Overall, correct saccade responses were faster in Single Saccade trials compared with Dual-Action trials, indicating general dual-action costs ($F(1,47) = 20.85, p < .001, \hat{\eta}_p^2 = .307$). The significant main effect of CSI indicated faster responses with increasing CSI ($F(1.83,86.22) = 597.92, p < .001, \hat{\eta}_p^2 = .927$). Critically, the interaction between Response Demand and CSI was significant too ($F(2.46,115.70) = 17.38, p < .001, \hat{\eta}_p^2 = .270$). A simple main effect analysis revealed that the effect of CSI was significant in both Single Saccade trials ($F(3,47) = 313.48, p < .001, \hat{\eta}_p^2 = .952$) and Dual-Action trials ($F(3,47) = 260.13, p < .001, \hat{\eta}_p^2 = .943$). Saccade Dual-Action RTs did not significantly differ from Single Saccade RTs at the shortest CSI duration of 100 ms (i.e., no significant dual-action costs, $p = .710, \hat{d}_z = -0.055$). At the remaining CSI durations of 400 ms, 700 ms and 1500 ms, saccades were significantly slower in Dual-Action trials than in Single Saccade trials (i.e., dual-action costs, all $ps < .001$, all $\hat{d}_z s > 0.55$).

Manual RTs. Both the main effect of Response Demand ($F(1,47) = 24.68, p < .001, \hat{\eta}_p^2 = .344$) and the main effect of CSI ($F(1.83,86.17) = 617.31, p < .001, \hat{\eta}_p^2 = .929$) were significant, indicating overall dual-action costs and a reduction of RT with increasing preparation time. The interaction between Response Demand and CSI was significant as well ($F(2.39,112.48) = 10.28, p < .001, \hat{\eta}_p^2 = .179$), driven mainly by larger dual-action costs at the two longer CSIs of 700 ms and 1500 ms (comparable to the pattern observed in saccade RTs).

Exploratory analysis: Saccade RTs including false positives

In an exploratory analysis, we compared the RTs of false-positive saccades in Single Manual trials with correct saccade RTs in Single Saccade trials and in Dual-Action trials. This analysis of error RTs was limited to the saccade modality since false-positive button presses

rarely occurred, preventing any meaningful RT analysis.[2] To avoid redundancies with the

analysis of correct RTs only the relevant differences between correct and error RTs are reported

here. False-positive saccades in Single Manual trials (M = 412 ms, SD = 163 ms) were, across all

CSIs, slower than correct saccades in both Single Saccade (M = 304 ms, SD = 116 ms, $p < .001$,

$\hat{d}_z = 0.854$) and Dual-Action trials (M = 324 ms, SD = 103 ms, $p = .001$, $\hat{d}_z = 0.689$).

Furthermore, while the simple main effect of CSI was significant for correct saccade RTs in both

Single Saccade trials as well as in Dual-Action trials (see correct RT analysis above), there was

no significant simple main effect of CSI on false-positive saccade RTs in Single Manual trials

$(F(3,28) = 1.94, p = .145, \hat{\eta}_p^2 = .172)$.

Discussion

Experiment 1 demonstrated inhibition-based dual-action benefits in error rates in the

oculomotor modality and (to a lesser extent) in the manual modality (Huestegge & Koch, 2014;

Raettig & Huestegge, 2018, 2021).[3] Crucially, a prolongation of preparation time led to

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[2] Note that false-positive saccades were quite infrequent as well at the longer CSIs. 19

participants had to be excluded from the analysis because of an absence of false-positive saccades

in any cell. For the remaining 29 participants, the average number of trials from which the error

RT mean was computed ranged from 16.90 at the CSI of 100 ms to 3.88 at the CSI of 1500 ms.

The results of this analysis should thus be treated with caution.

[3] Additional repeated-measures ANOVAs on saccade and manual error rates and RTs with the

within-subject factors Response Demand (Single-Manual, Single-Saccade, Dual); CSI (100 ms,

400 ms, 700 ms, 1500 ms), and Previous CSI (100 ms, 400 ms, 700 ms, 1500 ms) revealed,

abolished dual-action benefits in saccades and manual responses at the longest preparatory

interval (1500 ms). Participants were clearly able not only to prepare for the execution of the

currently relevant response type (indicated by reduced RTs with longer preparation time), but

also to prepare for inhibition of the currently unwarranted response type. This effect was

observed even though the cue did not entail information regarding response direction (i.e., it was

not a fully specified response that was inhibited, contrary to inhibition phenomena in the stop-

signal paradigm (Aron & Verbruggen, 2008; Matzke et al., 2018). Taken together, the results

strongly confirm the predictions of the *flexibly-targeted inhibition* account, according to which

inhibitory control can selectively operate at the level of response types (here: responses made

with one of two effector systems).

Even though dual-actions were, overall, slower than single actions in both modalities

(representing dual-action costs in RTs), the dual-action benefits in the accuracy data cannot

simply be ascribed to a mere shift in a speed-accuracy tradeoff, since dual-action costs in RTs

were smallest (or even absent) in the condition with the highest dual-action benefits in errors (100

ms CSI duration). The pattern of false-positive errors and their reduction with prolonged

preparation time was, overall, qualitatively comparable between the saccade and the manual

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except for the main effect in manual RTs ($F(2.69, 126.28) = 7.99$, $p < .001$, $\hat{\eta}_p^2 = .145$), no

significant main effect of (or interaction effect including) Previous CSI (all Fs < 2.42, all ps $>$

.073, all $\hat{\eta}_p^2$s $< .049$). This is at odds with the differential effects of variable and constant

foreperiods commonly observed in temporal preparation (Niemi & Näätänen, 1981).

modality, however it was more pronounced in saccades given the greater action prepotency of this particular effector system (Kürten et al., 2022).

Interestingly, in the manual modality, we did not only find a dual-action benefit in terms of more false-positive manual button presses in Single *Saccade* trials (vs. errors in Dual-Action trials). We also observed more frequent false-negative and directional manual errors in Single *Manual* trials (vs. errors in Dual-Action trials). This cannot be ascribed to an occasional global inhibition of all responses followed by a delayed re-start of manual response initiation (global inhibition account). Instead, there was a specific inhibition of only the saccade responses (e.g., Aron & Verbruggen, 2008; Bisset & Logan, 2014). A subsequent exploratory analysis of incorrect RTs of false-positive saccades revealed that inhibition failures were, overall, slower than correct saccade responses under single-action and dual-action conditions (except at the shortest preparatory interval of 100 ms). Additionally, error RTs were not significantly affected by prolongation of preparation time. This indicates that instances of failed inhibition might not simply be impulsive responses that were initiated too early to be overridden by inhibitory control but rather the result of confusion (i.e., crosstalk) among response-relevant codes that led to the formation of an inappropriate action plan.

Table 1

Descriptive Summary Statistics of Experiment 1 and Experiment 2

	CSI (ms)	Saccade Modality					Manual Modality				
		Single Manual	Single Saccade		Dual		Single Manual		Single Saccade	Dual	
		ER (%)	ER (%)	RT (ms)	ER (%)	RT (ms)	ER (%)	RT (ms)	ER (%)	ER (%)	RT (ms)
Experiment 1	100	29.46 (14.49)	3.29 (5.98)	462 (83)	3.69 (6.65)	459 (74)	3.58 (4.40)	639 (101)	2.88 (2.84)	0.98 (1.62)	684 (141)
	300	15.33 (12.94)	3.42 (6.03)	294 (69)	3.17 (5.79)	318 (64)	2.33 (3.34)	471 (94)	2.40 (3.35)	0.73 (1.28)	522 (132)
	700	9.75 (9.15)	3.67 (6.77)	234 (52)	3.58 (6.14)	271 (63)	1.73 (3.41)	415 (83)	1.50 (1.87)	0.94 (1.81)	489 (128)
	1500	8.23 (10.27)	4.04 (6.23)	215 (36)	4.25 (6.29)	248 (48)	1.29 (3.26)	393 (77)	0.98 (1.63)	1.08 (2.25)	478 (125)
Experiment 2	100	24.02 (15.64)	1.56 (3.82)	418 (74)	0.85 (1.77)	420 (64)	1.83 (2.94)	579 (102)	2.83 (3.56)	0.60 (0.96)	622 (133)
	300	12.96 (11.27)	1.46 (2.89)	266 (65)	1.15 (2.64)	278 (65)	1.44 (1.97)	438 (94)	1.79 (2.03)	0.67 (1.02)	500 (131)
	700	11.96 (10.04)	1.27 (4.21)	234 (63)	1.50 (4.13)	258 (62)	1.71 (1.93)	399 (87)	1.33 (2.08)	0.98 (1.16)	476 (121)
	1500	11.02 (8.82)	1.27 (2.53)	242 (53)	1.60 (1.99)	280 (63)	1.69 (2.75)	416 (88)	1.42 (2.29)	0.94 (2.20)	526 (153)

Note. Mean error rates (ER, in %) and reaction times (correct RT, in ms) of saccades and manual responses as a function of Response Demand (Single Manual, Single Saccade, Dual) and CSI (100 ms, 300 ms, 700 ms, 1500 ms) (SDs in parentheses).

Experiment 2

In Experiment 2, we aimed to generalize the findings of Experiment 1 and to control for any potential effects of sequential trial-by-trial mechanisms regarding CSI durations. To this end, CSI was held constant within (and instead varied between) blocks of trials.

Method

Participants

Forty-eight (60% female, 92% right-handed) new participants (mean age = 23.90 years, SD = 2.83 years) were recruited for Experiment 2. Based on the same exclusion criteria as in Experiment 1, the data set of one participant was excluded because of missing data and later recollected with the help of a new participant. Data were collected from 02-01-2022 to 05-30-2022.
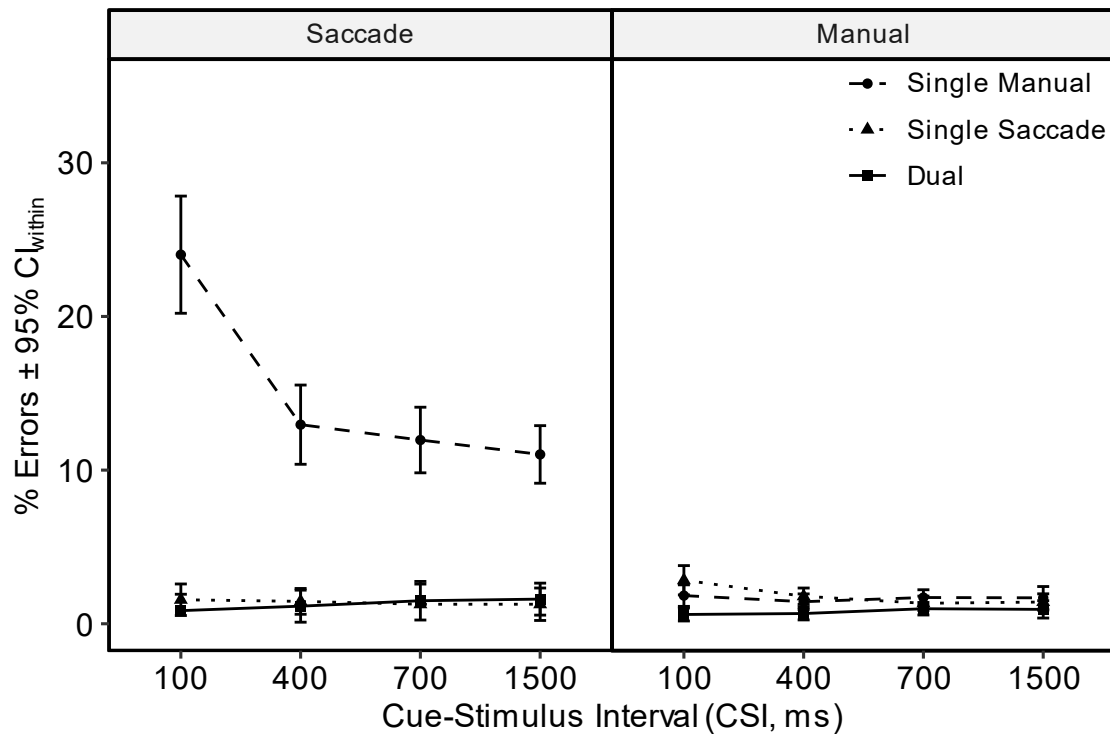
Apparatus, stimuli, procedure, and design

Experiment 2 was largely comparable to Experiment 1 except for the mode of the CSI manipulation which was now varied between blocks. To ensure the same number of trials per condition, however, the trials were now organized in 12 blocks of 60 trials each (instead of 10 blocks of 72 trials each). In every block, each cue type was again equally likely. Participants worked through 3 consecutive blocks of each CSI duration with the order of CSI durations fully counterbalanced across participants. Each session began with a practice block containing 24 trials with the first CSI duration encountered in the actual experiment that were removed from all analyses. The actual experiment consisted of 720 trials in total (60 per condition, 30 per condition

and direction), equivalent to Experiment 1. We analyzed the data in the same way as in

Experiment 1.

Results and Discussion

Data treatment

Applying the same criteria as in Experiment 1, we removed premature responses (RTs <

50 ms) from all analyses (0.15% of all trials). From correct RT analyses, we removed trials

containing any type of response error (6.78% of all trials) as well as RTs deviating more than ± 3

SDs from the individual cell mean (0.14% of all trials).

Error Data

Figure 3

Error rates (%) of Experiment 2

Note. Error Rates (%) in the oculomotor and manual modalities as a function of Response

Demand (Single Manual, Single Saccade, Dual) and CSI (100 ms, 400 ms, 700 ms, 1500 ms).

CSI was held constant within blocks and varied between blocks. Error bars represent the 95%

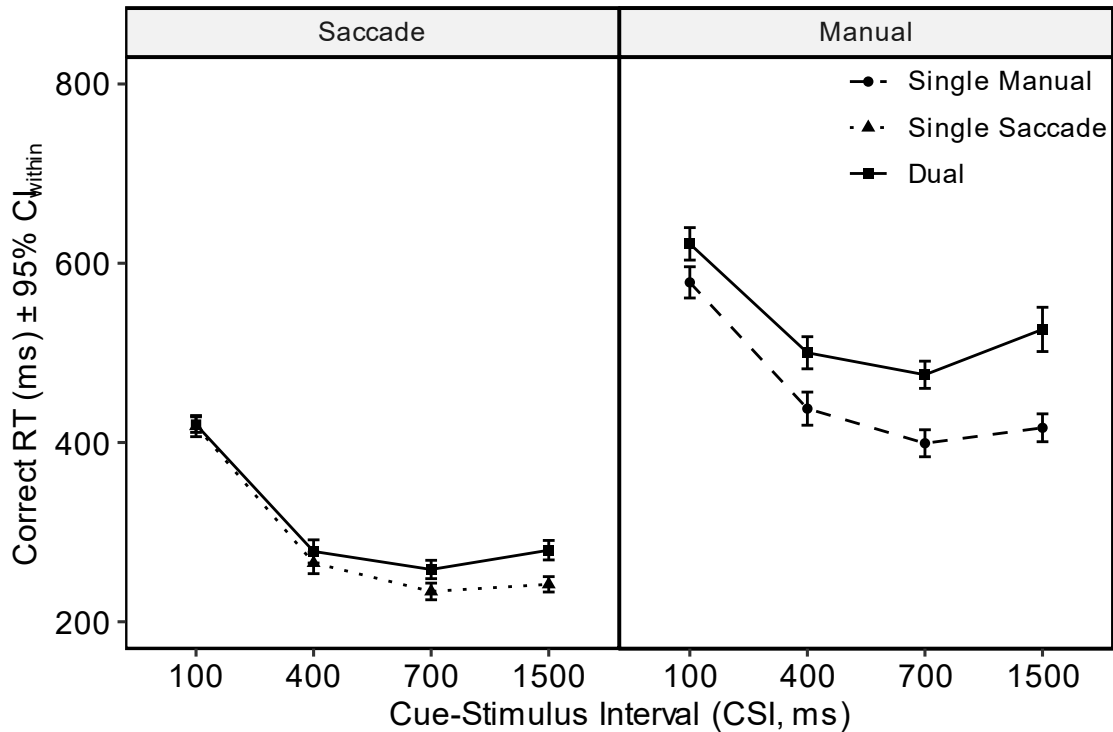CI$_{within}$ following Cousineau-Morey corrections.

Figure 4 depicts saccade and manual trial-level accuracy in the form of error rates.

Complete descriptive summary statistics can be obtained from Table 1.

Saccade errors. The significant main effect of Response Demand indicated dual-action

benefits ($F(1.05, 49.24) = 116.39, p < .001, \hat{\eta}_p^2 = .712$).Errors were, overall, more frequent in

Single Manual trials (14.99 %) compared with Single Saccade trials (1.39 %, $p < .001$, $\hat{d}_z = 1.602$) and, importantly, Dual-Action trials (1.28 %, $p < .001$, $\hat{d}_z = 1.571$). Error rates did not differ significantly between Single Saccade and Dual Action trials ($p > .999$, $\hat{d}_z = 0.074$). The main effect of CSI was significant as well ($F(2.00, 94.23) = 91.63$, $p < .001$, $\hat{\eta}_p^2 = .661$), indicating a reduction of error rates with increasing preparation time. Crucially, there was a significant interaction of Response Demand and CSI ($F(2.12, 99.47) = 24.64$, $p < .001$, $\hat{\eta}_p^2 = .344$). Simple main effect analyses revealed that the effect of CSI was significant only in Single Manual trials ($F(3,47) = 17.88$, $p < .001$, $\hat{\eta}_p^2 = .522$), but neither in Single Saccade trials ($F(3,47) = 0.31$, $p = .816$, $\hat{\eta}_p^2 = .019$), nor in Dual-Action trials ($F(3,47) = 2.17$, $p = .103$, $\hat{\eta}_p^2 = .122$). This indicates a specific preparatory benefit for inhibition performance in saccades. Bonferroni-adjusted post-hoc comparisons revealed significant dual-action benefits at all CSI durations (all $ps < .001$, all $\hat{d}_z s > 1.017$), however strongly decreasing in magnitude (from 23.17 percentage points at the 100 ms CSI to 9.42 percentage points at 1500 ms).

Manual errors. The significant main effect of Response Demand indicated overall dual-action benefits ($F(2.00, 93.96) = 10.46$, $p < .001$, $\hat{\eta}_p^2 = .182$). As in Experiment 1, error rates were higher both in Single Saccade trials (1.84 % false-positive button presses) and in Single Manual trials (1.67 % false-direction or false-negative button presses) compared with Dual-Action trials (0.80 % false-direction or false-negative button presses, both $ps < .002$, both $\hat{d}_z s > 0.522$). Error rates did not differ significantly between Single Saccade and Single Manual trials ($p > .999$, $\hat{d}_z = -0.106$). The main effect of CSI was not significant ($F(2.63, 123.47) = 1.85$, $p = .149$, $\hat{\eta}_p^2 = .038$), indicating no significant overall reduction of manual error rates with increasing preparation time. The interaction of Response Demand and CSI was significant ($F(3.88, 182.33) = 2.61$, $p = .039$, $\hat{\eta}_p^2 = .053$). However, simple main effect analyses revealed

that no effect of CSI in any of the Response Demand conditions was significant (all Fs < 2.65, all

ps > .060, all $\hat{\eta}_p^2$s < .145). Nevertheless, regarding false-positive button presses in Single

Saccade trials, there was a numeric trend toward fewer errors as preparation time increased (see

Table 1). Furthermore, Bonferroni-adjusted post-hoc comparisons for inhibition-based dual-

action benefits (i.e., comparing false-positive errors in Single Saccade trials with errors in Dual-

Action trials) showed significant dual-action benefits at CSIs of 100 ms and 400 ms (both ps <

.002, both $\hat{d}_z$s > 0.522) but not at CSIs of 700 ms and 1500 ms (both ps > .532, both $\hat{d}_z$s <

0.199).

RT data

Figure 4

Correct RTs of Experiment 2

Note. Mean correct RTs (ms) in the oculomotor and manual modalities as a function of

Response Demand (Single Saccade, Single Manual, Dual) and CSI (100 ms, 400 ms, 700 ms,

1500 ms). CSI was held constant within blocks and varied between blocks. Error bars represent

the 95% CI$_{within}$ following Cousineau-Morey corrections.

Figure 4 displays mean RTs in both modalities as a function of Response Demand and CSI

(100 ms, 400 ms, 700 ms, 1500 ms). Table 1 contains descriptive summary statistics.

Saccade RTs. We found a significant main effect of Response Demand ($F(1,47) = 22.30$,

$p < .001$, $\hat{\eta}_p^2 = .322$), indicating the presence of dual-action costs overall. Saccades were, across

CSIs, slower in Dual-Action trials compared with Single Saccade trials. The main effect of CSI was significant as well ($F(2.65,124.33) = 288.35, p < .001, \hat{\eta}_p^2 = .860$) indicating a strong reduction in saccade RT with increasing preparation time. The interaction of Response Demand and CSI was significant, too ($F(2.44,114.86) = 9.74, p < .001, \hat{\eta}_p^2 = .172$) and was mainly driven by stronger dual-action costs at longer CSIs compared with shorter CSIs. Dual-action costs were non-significant at the CSIs of 100 ms and 400 ms (both ps $> .098$, both $\hat{d}_z$s < 0.247), but significant at the CSIs of 700 ms and 1500 ms (both ps $< .001$, both $\hat{d}_z$s > 0.753).

Manual RTs. The same basic pattern as in saccade RTs emerged in manual RTs. Overall, manual responses were slower in Dual-Action trials compared with Single Manual trials as indicated by the significant main effect of Response Demand ($F(1,47) = 47.56, p < .001, \hat{\eta}_p^2 = .503$). Manual responses became faster with increasing preparation time ($F(2.65,124.33) = 288.35, p < .001, \hat{\eta}_p^2 = .860$), and there was a significant interaction of Response Demand and CSI, indicating that dual-action costs increased with increasing CSI duration ($F(2.44,114.86) = 9.74, p < .001, \hat{\eta}_p^2 = .172$). Dual-action costs were significant at all CSI durations (all ps $< .001$, all $\hat{d}_z$s > 0.542).

Saccade RT data including false positives

The comparison of (false-positive) error RTs and correct RTs was again conducted for

saccades only because of infrequent false-positive button presses.[4] False-positive saccades in

Single Manual trials (M = 412 ms, SD = 163 ms) were, across CSIs, slower than correct saccades

in both Single Saccade (M = 304 ms, SD = 116 ms, $p < .001$, $\hat{d}_z = 0.914$) and Dual-Action trials

(M = 324 ms, SD = 542 ms, $p < .001$, $\hat{d}_z = 0.856$). The simple main effect of CSI was

significant in correct saccade RTs in both Single Saccade trials as well as in Dual-Action trials

(see above), but not in error RTs ($F(3,34) = 0.20$, $p = .899$, $\hat{\eta}_p^2 = .017$).

Discussion

The results of Experiment 2 qualitatively replicated those in Experiment 1. This suggests

that, by and large, the same preparatory strategies and processes were involved regardless of

whether the CSI was varied in a trial-by-trial manner or held constant within blocks. Quantitative

differences (in terms of generally lower error rates and RTs in Experiment 2) might be

attributable to general effects associated with randomly varying CSI durations in Experiment 1

rather than to specific differences in preparatory strategies employed by participants (Los, 1996).

Overall, performance again benefited substantially from prolonged preparation time. Correct RTs

steadily decreased as CSI duration increased. However, this occurred to a greater extent in single-

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[4] 13 participants had to be excluded from the analysis for absence of false-positive saccades in at

least one cell. For the remaining 35 participants, the average number of trials from which the

error RT mean was computed ranged from 13.50 at the CSI of 100 ms to 6 at the CSI of 1500 ms.

action trials (Single Saccade and Single Manual) compared with dual-action trials, thus resulting

in (stronger) dual-action costs at longer CSI durations. Most importantly, however, the strong

effect of preparation time on the frequency of false-positive errors in both modalities was

replicated. Inhibition failures (and thus dual-action benefits) again decreased in saccades and

virtually vanished in manual responses as CSI was prolonged, strongly indicating that

participants effectively used the preparatory interval not only for activating required action

representations (executive control) but also for inhibiting unwarranted action (type)

representations (inhibitory control targeted at the level of effector system representations, not at

the level of a fully specified response). Thus, these data again corroborate the *flexibly-targeted*

inhibition account.

Again, the observed accuracy-related dual-action benefits cannot simply be explained as a

mere shift within a speed-accuracy trade-off, since dual-action costs in RTs were smaller in

conditions with larger dual-action benefits in error rates. As in Experiment 1, the exploratory

analysis of error RTs involving false-positive saccades revealed that such inhibition failures,

overall, occurred later than a correct response would have occurred, except for the shortest

preparatory interval and were not significantly affected by preparation time. This again suggests

considerably prolonged processing in trials containing a false-positive (saccade) response due to

crosstalk between response-relevant representations. Comparable to Experiment 1, manual dual-

action benefits also occurred in terms of a higher frequency of false-*negative* errors (i.e., button

presses that were *not* executed when required) in Single Manual trials compared with Dual-

Action trials.

General Discussion

The aim of the present study was to examine the temporal dynamics of inhibitory control processes by manipulating preparation time in a task that required frequent switching between single-action execution (*either* saccade *or* manual) and dual-action execution (saccade *and* manual). Crucially, execution of the single manual action required a costly (i.e., often failing) inhibition of the highly prepotent saccade response, and even single saccade execution required inhibition of manual responses to some degree (as indicated by corresponding dual-action benefits regarding response accuracy in conditions with minimal preparation time). Dual-action requirements were easier to follow than the single-action requirements due to the absence of concurrent inhibitory demands. The focus of the present analyses was on the effect of preparation time (CSI duration) on the inhibitory processes (and their failure) underlying dual-action benefits in multiple action control. The main findings can be summarized as follows.

Summary of the main findings

Overall, both experiments provided further support for the robustness of inhibition-based dual-action benefits (or single-action costs, respectively) in terms of a greater overall response accuracy in dual-action trials compared with single-action trials (Huestegge & Koch, 2014). These dual-action benefits were observed in saccades and manual responses, indicating that the same basic mechanism is responsible for inhibition failures in both modalities, however, more prominent in saccades compared with manual responses, likely due to a greater prepotency of saccades to be executed to suddenly occurring peripheral stimuli.

Crucial for the main goal of the present study, however, was the observed effect of CSI on performance. In both experiments, participants were able to make effective use of a prolonged preparation time for both executive and, most critically, inhibitory control. RTs generally

decreased as a function of preparation time, as is commonly observed, for example, in studies

using the cued task-switching paradigm (e.g., Kiesel et al., 2010; Meiran, 1996). This RT

decrease was even observed in trials involving concurrent inhibitory and executive control (e.g.,

Single Manual trials), indicating that preparation did not entail *global motor inhibition*. Most

important, however, is that an increase in preparation time had a clear-cut effect on the frequency

of false-positive executions of saccade (manual) responses in trials requiring the sole execution of

a manual (saccade) response. Such inhibition failures were more effectively prevented with

increasing preparation time even though the cue only provided advance information of relevant

response *modalities* instead of *fully specified responses* (Rosenbaum, 1980; Rosenbaum &

Saltzman, 1984). Specifically, there was a sharp decline in inhibition failures (especially in the

saccade modality) when increasing the CSI duration from 100 ms to 400 ms, with a smaller

incremental reduction at the CSI of 700 ms. False-positive (saccade) errors eventually reached an

asymptotic minimum at the longest CSI of 1500 ms, suggesting that the present range of CSI was

well-chosen to exhibit the dynamics of the effect. Such a clear-cut effect on false-positive errors

renders a highly targeted inhibition at the level of effector system representations the most likely

explanation for the present results. At the same time, however, prolonging the CSI had no effect

on (already low) error rates in dual-action trials (in neither of the two modalities). Therefore,

increasing CSI duration led to a pronounced decrease (even an extinction in manual responses) of

dual-action performance benefits. Dual-action *benefits* in accuracy went hand in hand with dual-

action *costs* in RTs, at least at the longer CSI durations. However, this cannot be interpreted as a

shift in the speed-accuracy trade-off as the sole explanation for accuracy-related dual-action

benefits, since we observed the strongest dual-action benefit in the condition with the smallest

dual-action costs in RTs.[5] In fact, the rather small dual-action costs (especially in saccades and at the shortest CSI duration) might even reflect another source of a dual-action benefit than the absence of inhibitory demands, namely a true beneficial effect of being allowed to perform two redundant responses (Raettig & Huestegge, 2022). Much as redundant stimulus information (e.g., in congruent trials of the Simon task, Simon & Rudell, 1967) can facilitate responding compared to a situation without such redundant information (Ulrich et al., 2015), executing one action might facilitate execution of a concurrent, highly code-compatible action in dual-action trials but not in single-action trials. Still, dual-actions in the present study were easier to execute mainly due to the strong response commission bias in single-action trials and not due to more efficient (i.e., faster) dual-action (vs. single-action) execution (but see Raettig & Huestegge, 2021, 2022 for dual-action *RT* benefits).

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[5] Note that there was no restriction on the inter-response-interval (IRI) for dual-action trials to be counted as 'true' dual actions but participants were instructed to carry out both responses simultaneously in dual-action trials. In principle, small dual-action RT costs, especially in saccades at the shortest CSI duration, could have been caused by fast guesses, essentially false-positive 'single-saccades' followed by a delayed manual response. This is unlikely, however since the occasional occurrence of such 'sequential single-actions' would have led to a bimodal distribution of IRIs which we did not observe. Unimodal and uniform IRI distributions in both experiments and across all CSI durations (see Figures S5 and S6 in the supplementary material) indicate that 'true' dual actions were carried out in the great majority of trials.

Furthermore, exploratory analyses of RTs of saccadic inhibition failures revealed, overall, relatively long error latencies compared with correct RTs and, importantly, no significant effect of CSI duration. Therefore, while being faster than (Experiment 1) or not significantly different in speed (Experiment 2) from the slowest correctly executed saccades at the shortest preparatory interval (100 ms), false-positive saccades were consistently slower than correctly executed saccades at all other interval durations. Error RTs were also not affected by the manipulation of preparation time. Thus, false-positive errors (especially saccades) cannot (generally) be considered as mere reflexes triggered by the onset of the peripheral target that could not be overridden fast enough by inhibitory control. Instead, instances of inhibition failures might represent the result of a time-consuming but ultimately ineffective attempt to resolve crosstalk between response-relevant codes. It is important to note that due to potential biases in samples consisting mainly of young, white academics, the present findings may not be generalizable to other populations or contexts, such as individuals from different age groups, racial or ethnic backgrounds, or levels of education and socioeconomic status, which may exhibit different cognitive processes or respond differently to experimental manipulations.

The benefit of preparation: reduced dual-action benefits

Beneficial effects of having sufficient preparation time on performance have already received numerous support in the literature (Kiesel et al., 2010; Niemi & Näätänen, 1981). In contrast to the intuitiveness of these findings, the exact nature of the preparatory mechanisms in the current setting is much less obvious. Here, the important question is how exactly preparation in the present setting helped to reduce the frequency of inhibition failures in the unwarranted action modality while simultaneously allowing for speeded responding in the required action modality. The current results indicate that participants were able to selectively inhibit
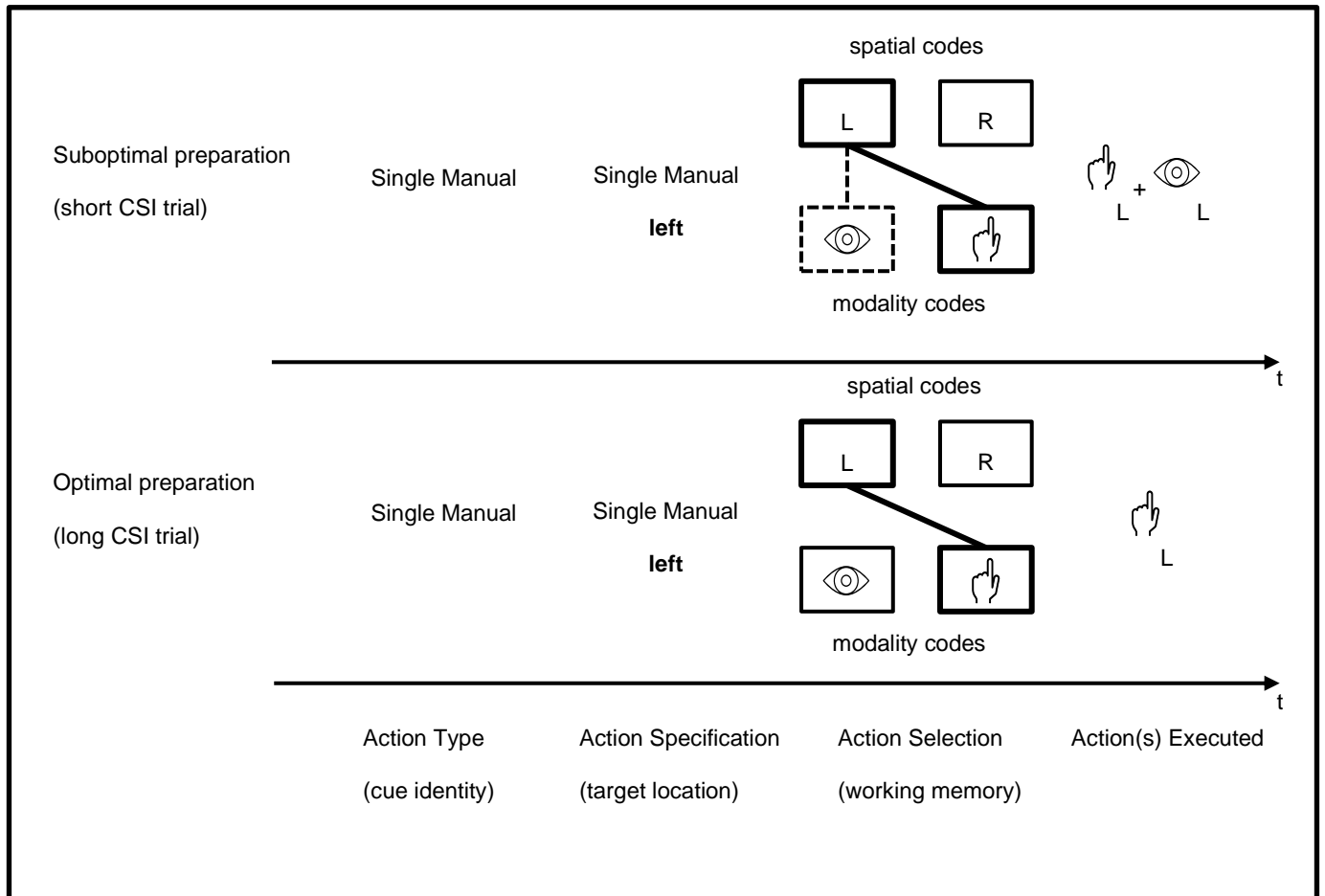
(downregulate) activity of an effector system without substantially affecting the functioning of the other effector system, demonstrating that inhibition can be flexibly targeted at the level of action type representations (*flexibly-targeted inhibition account*). Of course, the beneficial effects of such a preparatory strategy can only unfold after the cue has been processed, and this process might not be completed early enough at shorter CSIs (especially at 100 ms), yielding high rates of inhibition failures (see Figure 5). In such a case of insufficient preparation time, participants would have to resort to a more error-prone inhibition of the unwarranted response concurrently with the activation of the required response. It is important to note that, within the framework of multiple action control by Huestegge and Koch (2010, see introduction section), the present data could be explained by inhibition of all potential bindings between modality codes and spatial codes (i.e., targeting all specific responses in one effector system) instead of inhibition of the modality code *per se*.[6] However, these two mechanisms are not mutually exclusive and could well work in conjunction. Therefore, it is difficult to ascertain their relative contributions based

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[6] This, in fact, resembles another potential explanation completely foregoing the notion of inhibitory control (see MacLeod et al., 2003 for a critique of cognitive inhibition as an explanatory concept). One might explain the reduction of false-positive saccade (manual) errors by assuming a cutting of the link between input activation provided by the target stimulus and the currently unwarranted action modality (for a model of inhibitory control in terms of blocked input, see Logan et al., 2015). However, even such a "non-inhibitory" preparatory mechanism would need to act on specific effector system representations without affecting others (and before a response is fully specified) to eventually produce the current results.

on the present data. Importantly, however, this does not compromise our interpretation of

flexibly-targeted inhibition at an intermediate level (between global motor inhibition and

inhibition of one fully specified response), since both inhibitory mechanisms would need to act

on one effector system (and/or its associated responses) but not another.

Figure 5

Processing of a Single Manual trial from cue onset (indicating action type demand, left) to action execution (right) under suboptimal and under optimal preparation.

Note. Under suboptimal preparation, the saccade modality is activated and bound into the action plan producing a false-positive error while under optimal preparation, the saccade modality can be inhibited during preparation without affecting the performance of the manual modality. Only a flexibly-targeted inhibition of responses made with one effector system following cue processing but prior to full action specification would lead to such a result.

The interpretation in terms of targeted inhibitory control at the level of effector system representations (or a small array of potentially prepotent responses within this effector system) as opposed to global motor inhibition or inhibition of a fully specified response expands studies on partial cueing of response components to be executed based on partial preparation for responses to be inhibited at the same time (Rosenbaum, 1980; Rosenbaum & Saltzman, 1984). Furthermore, it is well in line with (and extends) previous findings on both reactive and proactive inhibition. In a sequential stop-signal study, it has been demonstrated that following the inhibition of one specific response (e.g., left button press) in Trial N-1, the execution of any button press (i.e., left or right) was delayed and the inhibition of any button press was facilitated in Trial N (Giesen & Rothermund, 2014). Similarly, a proactive inhibition study by Muralidharan et al. (2019) showed that preparation facilitated the selective inhibition of a response with one hand at the expense of a delayed response execution with another hand. These findings suggest that inhibitory control might act on a *more* global level than that of fully specified responses only. Previous findings within the SDS paradigm (which, unlike the studies mentioned above, employed two response modalities) demonstrated that action prepotency (and thus the rate of false-positive errors) was elevated in a Trial N following a requirement in Trial N-1 to execute the action that now (in Trial N) needed to be suppressed (Kürten et al., 2022). Importantly, this transient increase in action prepotency depended mainly on which action *modality* (e.g., "saccade") was required in the previous trial, not on the fully specified action (e.g., "left saccade"). Analyses of sequential effects of response demand in the present experiments showed a similar pattern (see supplemental material for figures and full results). Inhibition failures (in both modalities were starkly reduced following a (successful) inhibition (vs. execution) of the same modality in the previous trials. While this effect was sometimes stronger if the *exact* same action had to be inhibited again, even the inhibition of the opposite direction was substantially facilitated following an inhibition (vs.

execution) in the previous trial. Again, this suggests that inhibition can act *more* globally than on a fully specified action alone. Taken together, it therefore seems natural to conclude that participants prepared for inhibitory control demands by proactively decreasing prepotency (i.e., pre-activation) specifically of the modality representation, thereby further supporting our model assumption of a distinct modality representation in the working memory-based representation network.

The assumption of distinct action modality representations and their activations' malleability prior to the actual mapping selection process is consistent with findings from other domains showing the important role of effector system representations in multiple action control. For example, it has been demonstrated that effector systems are an important determinant of response order in the PRP paradigm and must therefore be represented well before actual response execution (Pieczykolan & Huestegge, 2019). Furthermore, the present experimental setup bears some obvious resemblance to the pre-cued task-switching paradigm (see Kiesel et al., 2010; Vandierendonck et al., 2010 for reviews). One important explanation of preparation effects in task-switching typically refers to an active reconfiguration of the task set (including stimulus representations and attentional weightings, see Vandierendonk et al., 2010). We do not wish to imply that the three response demands relevant in the current study (Single Manual, Single Saccades, Dual) are each necessarily represented as individual tasks in the typical sense within the task switching literature. However, when assuming a hierarchical task set in which sometimes only a few parts need to be reconfigured (Kleinsorge, 2004; Kleinsorge & Heuer, 1999), and when assuming that action modality representations are an essential part of the task set (Koch et al., 2004), one can easily see how a minimal task-set reconfiguration in the present scenario could entail both the strengthening of currently relevant action modality representations (executive control) as well as the suppression of currently unwarranted modality representations (inhibitory

control). Of course, the specific mechanisms of such reconfiguration processes were already

highlighted in our mechanistic model described above.

Further theoretical considerations: Inhibitory mechanisms and individual differences

The present results demonstrated dual-action benefits rooted in the relative difficulties

associated with performing one action while simultaneously inhibiting another. The cost incurred

on single-action execution by concurrent inhibitory control demands was greatly reduced by

prolonging preparation time. On a general level, inhibitory control in the present context refers to

the suppression or removal of currently irrelevant action (modality) representations in (or from)

working memory (see above and e.g., Ecker et al., 2014; Gade et al., 2014; Oberauer, 2005). The

exact nature of the inhibitory processes involved, however, is more difficult to specify. Previous

studies using the SDS paradigm using manual and vocal actions have demonstrated evidence for

a specific inhibitory coding strategy of action selection adopted by participants under certain

specific conditions, namely the simultaneous presentation of cue and target as one integrated

stimulus. Participants appeared to prepare both actions on each trial, but inhibiting one particular

action of the two when a single action was required (Raettig & Huestegge, 2021). In a sense,

participants then coded a single action in terms of not executing the other action (inhibitory

coding of single action execution). Apart from the accuracy-related dual-action benefits observed

here, this strategy (in such specific situations) has even led to significant dual-action benefits in

(manual) RTs, potentially due to an initial global stop or pause process and a subsequent

cancellation of the unwarranted response (e.g., Diesburg & Wessel, 2021). In the present study,

this was not observed even though there was a lack of significant dual-action costs in RTs in

some CSI conditions. While it is conceivable that participants used an inhibitory coding strategy

of single actions with a dual-action default, especially at the shortest CSI and in Experiment 2

(constant CSIs) where the cue might not have been processed fast enough to engage in proactive

inhibition of the unwarranted response, we do not claim that this was necessarily done in every

condition.

To further pinpoint the inhibitory mechanisms underlying the present finding of dual-

action benefits in accuracy data, it is of interest to examine the nature of inhibition failures more

closely. The exploratory analyses of error RTs of false-positive saccades revealed that false-

positive saccades were considerably slower than correct saccade responses (in Single Saccade or

Dual-Action trials) at all but the shortest CSI durations. This is at odds with an independent race

account of inhibition traditionally used to explain performance in the stop-signal paradigm

(Logan, 1994, Matzke et al., 2018). The independent race model assumes that a go-process (e.g.,

execute left-saccade) triggered by the go signal and a stop-process (e.g., stop left-saccade)

triggered by a following stop signal run in parallel without mutual interference. This implies that

false-positive action executions will only occur in trials with particularly fast go-processes (e.g.,

reflexive saccades) that "escape" the stop process (Logan & Cowan, 1984). False-positive

responses should thus be, on average, faster than correct responses which was not the case in the

present study. Instead, our findings indicate that in the presence of concurrent executive action

demands in another modality as well as previous and future executive demands in the same

modality, failures of inhibition were the result of substantial processing efforts, potentially in a

failed attempt to discriminate between execution and inhibition requirements within one modality

(Bissett & Logan, 2014). Furthermore, the latency of false-positive saccades was largely

unaffected by the CSI manipulation, suggesting similar causes of false-positive errors at any CSI

duration (only occurring more frequently at the shortest preparatory interval due to the lack of

preparatory inhibition). The exact nature of the processes leading up to inhibition failures in the

face of ongoing action execution, however, are beyond the scope of the present data and considerations and require dedicated future studies.

Regardless of the exact mechanisms underlying inhibitory control and its failures (leading to the emergence of dual-action benefits in accuracy), based on the large standard deviations of false-positive errors (mainly in saccades) it is safe to assume strong inter-individual differences in the efficacy of these processes. The investigation of individual differences in inhibitory control has a long tradition in the fields of cognitive aging (e.g., Williams et al., 1999) and psychopathology (e.g., Schachar & Logan, 1990). Given that the sample of the current study consisted of young, healthy adults, a promising point of departure for explaining these differences in the present case is probably a set of studies that relate differences in inhibitory control performance to differences in working memory capacity (Engle et al., 1995; Redick et al., 2007). This calls for future studies assessing the propensity for dual-action performance benefits (based on differential inhibitory demands) as a function of working memory capacity. In addition, it would be interesting to investigate how elderly people or people with certain disabilities fare in the SDS paradigm, especially since it is unique in combining selective inhibitory control in the context of simultaneous executive action coordination at the same time.

Conclusion

To conclude, the present study warrants the following three take-aways. (1) It provided further support for the robustness of accuracy-related dual-action benefits and corroborated that inhibitory control difficulties in single-action conditions represent a root cause. In particular, inhibition failures in single-action trials were more frequent than errors of any type in dual-action trials in either modality, especially in short CSI conditions. (2) When given appropriate preparation time (based on information about which effector system will be relevant), the

frequency of such inhibition failures (and thus dual-action benefits) was greatly reduced (in saccades) or even completely cancelled out (in manual responses). The data suggest that inhibitory control of unwarranted actions was prepared in parallel to the execution of the required alternative action. (3) Since advance information provided by the action cue referred only to action modality (or modalities), not to a fully specified response such as in a typical stop signal situation, we propose that preparatory inhibition processes were targeted at a dedicated representation of an effector system (or at the array of prepotent responses within that effector system). In a sense, participants decreased their general tendency to respond with one, unwarranted, effector system while simultaneously increasing their tendency to respond with another, required, effector system. This particular inhibitory mechanism complements well-known other types, such as global inhibition, and inhibition of an already fully specified action program, thus highlighting the flexibility of cognitive control in general. Finally, the results also highlight the relevance of assuming a cognitive architecture involving (input and) output (effector system) representations for optimally processing a task at hand.

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