Towards a taxonomy of inhibition-related processes: A dual-task approach

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Abstract

The ability to inhibit responses is key to controlled behavior and is commonly investigated with the stop-signal paradigm. The authors investigated how response inhibition is situated within a taxonomy of control processes by combining multiple forms of control within novel dual tasks. Response inhibition, as measured by stop-signal reaction time (SSRT), was impaired when combined with shape matching, but not the flanker task, and when combined with cued task switching, but not predictable task switching, suggesting that response inhibition may be weakly or variably impaired when combined with selective attention and set switching demands, respectively. Response inhibition was consistently impaired when combined with the N-back or directed forgetting tasks, putative measures of working memory. Impairments of response inhibition by other control demands appeared to be driven by task context rather than evoked control demands, as SSRT slowing was similar for trials where control demands were either present (e.g., task switch) or absent (e.g., task stay). These results were initially identified in a discovery sample and subsequently validated in a pre-registered analysis of a held-out sample of subjects (N = 33 and 33, respectively). Taken together, these results show that response inhibition processes are often impaired in the context of other control demands, even on trials where direct engagement of those other control processes is not required. This suggests a taxonomy of control in which response inhibition overlaps with related control processes, especially working memory.

Keywords: Response inhibition, dual task, working memory, selective attention, task switching

Introduction

Cognitive control can be conceptualized as a set of processes that facilitate goal-directed behavior, and response inhibition is often characterized as one of these core processes (Friedman & Miyake, 2004; Logan, 1985). Hasher and colleagues (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999) suggest that different forms of control and interference resolution depend on a single function, perhaps inhibition. Friedman and Miyake (2004) suggest that prepotent response inhibition is a main control function that relates closely to resisting distractor interference but is distinct from resistance to proactive interference. Logan (1985) suggests that disengaging or inhibiting a thought or action is a fundamental act of control. Thus, across theoretical frameworks, inhibition is a central component of theories of control, but the relationship between inhibition and other acts of control is less well understood. Here we aim to characterize the relationship between inhibition and related acts of control.

Response inhibition is key to control as it is the last line of defense to control thoughts and actions. Controlled performance involves planning, retaining goals in memory, selecting between actions, and engaging action. However, goals can change at any time, such as when a pedestrian walks in front of one's car as they are driving. At this point, response inhibition becomes a necessary process to quickly arrest the current action (e.g., pull one's foot off the accelerator) and prepare to engage a new action (e.g., engage the brake).

The stop-signal paradigm (Logan & Cowan, 1984) is commonly used to measure response inhibition. At the beginning of each trial, a choice ("go") stimulus is presented that is usually mapped to one of two responses. On a subset of trials, a stop signal is presented after a stop-signal delay (SSD), which informs the subject to attempt to stop their choice go response. The dominant theoretical framework for understanding and analyzing stopping data is the Independent Race Model (Logan & Cowan, 1984; Logan, Van Zandt, Verbruggen, & Wagenmakers, 2014), which assumes that a go process is engaged when the go stimulus

occurs that races independently against a stop process that is engaged when the stop stimulus occurs, with going finishing first resulting in stop failure and stopping finishing first resulting in stop success. The Independent Race Model allows estimations of the latency of response inhibition, stop-signal reaction time (SSRT), which is the dominant measure in the stop-signal task. Slower SSRT is taken as worse response inhibition.

There is a distinction between two key types of independence that relate to the Independent Race Model: context independence and functional independence. The Independent Race Model assumes *context independence*, which means that the finishing time distribution of the go process is the same on go and stop trials. Recent work brings into question this assumption of context independence (Bissett, Jones, Poldrack, & Logan, 2021; Colonius, Ozyurt & Arndt, 2001; Gulberti, Arndt, & Colonius, 2014). We test this assumption and employ strategies to avoid violations. In contrast, the focus of this manuscript is whether go and stop are *functionally independent*, which means that the factors that influence the finishing times of the go process do not affect the finishing times of the stop process (and *vice versa*). Functional independence is not an assumption of the Independent Race Model and therefore violating functional independence does not invalidate the race model or the measures estimated from it, such as SSRT. We evaluate functional independence by asking whether control demands that influence going (like switching tasks, selective attention, and manipulating working memory representations) also influence stopping, namely by slowing SSRT.

One strategy to investigate the relationship between different control processes is to combine tasks into a dual task. The dual task logic (Pashler, 1994; Townsend & Ashby, 1983) assumes that if two tasks depend on overlapping and limited processes then the presence of a second task will impair the performance of the first task. However, if the processes of the two tasks are independent, the presence of a second task will not affect the performance of the first task. This could be understood as a resource limitation (Logan et al., 2014; Tombu & Joliceour, 2003; Townsend & Ashby, 1983), a bottleneck in processing capacity (Pashler, 1994) or any

other framework that assumes shared and limited processing. We do not commit to one of these frameworks nor do we attempt to adjudicate between them within this manuscript, but we do adopt the general logic that impaired dual-task performance provides evidence of the two underlying processes overlapping and sharing some form of limited processing or capacity.

In the literature, this dual-task approach has been implemented by combining the stop-signal task with other cognitive control tasks and measuring SSRT. This has yielded variable results. The most well-studied combination has been combining a stop signal with a distractor interference task, where a participant must respond to one stimulus, while suppressing a response to distractor stimuli. In a flanker task combined with a stop signal, SSRT increased in the presence of distractor stimuli (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Ridderinkhof, Band, & Logan, 1999). In a series of papers, Verbruggen and colleagues further explored this by replicating the original flanker findings and revealing similar SSRT slowing in the Stroop and global-local paradigms, but not in the Simon paradigm (Verbruggen Liefoghe, Notebaert & Vandierendonck, 2005; Verbruggen, Liefoghe, & Vandierendonck, 2004; Verbruggen, Liefoghe, & Vandierendonck, 2006a). Additionally, introducing stimulus-response incompatibility (press left when the stimulus indicates right) did not prolong SSRT (Logan & Irwin, 2000; van den Wildenberg & van der Molen, 2004). Taken together, most existing evidence suggests response inhibition is slowed when subjects also must selectively attend or resist distractor interference, consistent with an overlap in these two processes (Friedman & Miyake, 2004). However, mere stimulus-response incompatibility does not appear to impair response inhibition.

On the other hand, when a stop-signal task was combined with a task switching task, SSRT did not differ between task-stay and task-switch trials in simple stopping (Verbruggen, Liefoghe, Szmalec, & Vandierendonck, 2005) or selective stopping (Verbruggen, Liefoghe, & Vandierendonck, 2006a). This is in line with related work showing that when doing two tasks in rapid succession using a psychological refractory period (PRP) design (Pashler, 1994), that

SSRT does not suffer from such a refractory effect (Yamaguchi, Logan, & Bissett, 2012). This work suggests that response inhibition may be specifically separable from task switching and generally not susceptible to dual task costs.

There is mixed evidence as to whether response inhibition interacts with working memory demands including resisting proactive interference and updating. Bissett, Nee, and Jonides (2009) found no difference in SSRT in a directed forgetting task when stopping to probe stimuli that were and were not recently in memory, suggesting that updating and resisting proactive interference in working memory do not interact with response inhibition. Conversely, recent work by Boucher, Viparina, and Collins (2021) showed that SSRT was slower when doing a putatively more challenging working memory task (count backwards by two for each trial) than when performing an easier working memory task (counting forward by one for each trial). There is also a related literature that shows costs to memory performance after response inhibition (Chiu & Egner 2015a, Chiu and Egner, 2015b) and costs to memory performance after unexpected sounds that may engage response inhibition (Wessel & Aron, 2017).

Taken together, these varied findings motivate further investigation into how dual tasks can be used to understand the relationship between response inhibition and related control processes. Our proposed work advances on this existing work in three ways. First, instead of focusing on a single pair of tasks, we acquired a sample of subjects who each performed dual tasks that combined the stop-signal paradigm with seven tasks that capture various aspects of control including selective attention, working memory, and set switching. This allows us to develop a taxonomy of control processes from a single dataset that limits idiosyncratic differences in sample, stimuli, or implementation. Second, to evaluate the robustness of our results, we split our sample into a discovery dataset that was explored with various analytical techniques and a validation dataset that was untouched until a pre-registered analysis plan was completed. Results are considered robust and confirmed if they were revealed in both the initial discovery dataset and the pre-registered validation analysis.

Third, we designed this study to evaluate whether merely being in the context of a dual task may be sufficient to impair inhibition. Existing work has focused on comparing different trial types within a dual task - what we call “dual conditions”. For example, SSRT is compared between flanker congruent and flanker incongruent trials, with the latter being longer taken as evidence that the processes involved in resolving flanker interference (perhaps selective attention) interact with response inhibition. However, this approach is blind to any block- or task-level contextual challenges to dual tasking. Such costs may be related to task preparation costs (Pashler, 1994) and so called mixing costs which index impairment when two different single tasks are interspersed compared to completing the same single task repeated (Allport, Styles, Hsieh, 1994; Koch, Prinz, & Allport, 2005; Los, 1996). If preparing to selectively attend or the possibility of needing to selectively attend interacts with response inhibition, we would expect flanker congruent SSRT and flanker incongruent SSRT to both be prolonged compared to a canonical stop-signal task that does not involve the possibility of needing to selectively attend and resist distraction. In order to evaluate this possibility, we not only sampled a broad range of inhibition-related dual tasks, but we also ran a canonical simple stop-signal task. This allows us to supplement our analyses of dual conditions with what we call “dual context” effects, which are defined as an increase in SSRT in a dual-task context even on trials that do not putatively require the control process of interest (e.g., task-stay trials in a task switching task or flanker congruent trials in a flanker task) compared to SSRT on a traditional (non-dual) stop-signal task. This allowed us to evaluate whether the context of each specific dual task is sufficient to impair response inhibition, a potential result that would be masked in the existing literature by its focus on evaluating SSRT between two different trial types within a dual task, and not also between dual and single tasks.

Methods

Subjects

Data were collected using Amazon Mechanical Turk, as a part of a 10-12 hour, 36-task battery. We offered this study to all 279 Mechanical Turk workers who had previously completed both an initial battery of tasks and surveys (Eisenberg et al., 2019), and a follow-up study on political ideology (Zmigrod, Eisenberg, Bissett, Robbins, & Poldrack, 2021). We chose to recruit from this existing sample based on their known reliability as participants, and in order to open the opportunity to analyze these subjects across these three data acquisitions (though we do not do so in the present manuscript). Of the 279 workers contacted, 159 workers expressed interest in being involved in the study and were given access to the study tasks, and 100 workers completed at least one task. All participants who were contacted and expressed interest were allowed to participate. Tasks were coded using jsPsych (de Leeuw, 2015), and administered by Experiment Factory, a platform that allows participants to remotely complete tasks at their own pace over a period of time (Sochat, Eisenberg, Enkavi, Bissett, & Poldrack, 2016). Participants were given one week to finish the battery, with reasonable requests for extensions granted (mean: 4.48, standard deviation: 2, range: 1-10 days), and were paid \$4 per hour, with an additional \$4 per hour for completing the entire battery, for a total of \$96. Our final sample entails the 66 participants who completed the full battery. We focus this manuscript on the eight of the 36 tasks that involved stop signals.

Procedure. The eight tasks that are the focus of this manuscript are a traditional simple stop-signal task and seven dual tasks that were created by combining the simple stop-signal task with each of the following seven commonly used control tasks: go/no-go (Donders, 1868/1969), flanker (Eriksen & Eriksen, 1974), shape matching (Friedman & Miyake, 2004), n-back (Kirchner, 1958), directed forgetting (Bjork, 1972), and both cued and predictable task switching (Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Rogers & Monsell, 1995) (See Figure

1). In these seven dual tasks, the go task matched the demands of one of these seven paradigms, but on some trials a stop signal was presented and subjects were instructed to try to inhibit their response. Stop probabilities were equated across task conditions. The length of each task was variable. We aimed to have ~250 trials per task with no fewer than 20 trials per condition and no more than 50 trials per condition.

Figure 1: Task schematics. Visual stop signals (stars) were presented in all 8 tasks but stop signals are only shown in the first schematic. For each task, the response window began when the task stimuli replaced the inter-trial fixation cross, and persisted for 1000ms after the stimuli disappeared.

Stop signal: Participants were instructed to respond with an arbitrary response mapping to either a circle or a square presented on the screen based on the identity of the shape. On some trials, after a variable delay, a stop signal would appear. The stop signal in the simple stop task and all dual tasks was a 7-pointed star presented around the imperative stimulus. Participants were instructed to withhold their response when presented with a stop signal. Note that similar to the other tasks, the go stimuli was presented for 1000ms, regardless of the stop signal delay.

Cued Task Switching: Participants were instructed to respond to a number presented after a cue. If the cue was Parity or Odd-Even, the participants were instructed to respond whether the number was odd or even. If the cue was Magnitude or High-Low, they were instructed to respond whether the number was larger or smaller than 5. This four-to-two cue to task mapping allows us to distinguish task switch costs from cue switch costs (Logan & Bundesen, 2003; Mayr & Kliegl, 2003). The presented numbers were 1, 2, 3, 4, 6, 7, 8, and 9.

Predictable task switching: Participants were instructed to respond to a presented number moving clockwise through the four quadrants of the screen. If the number appeared on the bottom two quadrants of the screen, they were to judge the parity of the number. If the number appeared in the top two quadrants of the screen they were to judge the magnitude of the number (larger or smaller than 5). The presented numbers were 1, 2, 3, 4, 6, 7, 8, and 9.

Flanker task: Participants focused on a central letter flanked horizontally by four letters, two on each side. All letters were either F or H and all four flankers on each trial were the same, though the flankers sometimes matched (congruent) or mismatched (incongruent) the central probe. Subjects were instructed to respond with the F key if the center letter was F, and the H key if the center letter was H, and to ignore the four flanking letters.

Shape matching: Participants were asked to respond whether two shapes, one white (on the right side of the screen) and one green (on the left side of the screen), were the same or different. On some trials, a distractor red shape would appear superimposed on the green shape. Participants were instructed to ignore the red shape.

Directed forgetting task: Participants were presented with four letters. They were then instructed to forget either the top two, or bottom two, depending on the cue they saw, either TOP or BOT, respectively. They were then presented with a letter, and asked whether this letter was or was not present in the letters they were instructed to remember. Note that directed forgetting tasks can be implemented in a variety of ways (Bjork, 1972) and we have chosen an implementation that depends on encoding and manipulating working memory representations (Nee, Jonides, & Berman, 2007).

N-back: Participants were presented with a series of letters, and asked to respond whether the current letter matched or mismatched the letter n -trials ago, with “ n ” varying across blocks of trials between 1, 2, and 3.

Go No-go task: Participants were instructed to respond with a finger-press to a filled black square, but not respond to an unfilled black square.

The procedure for each of the eight tasks was similar. Participants would receive 1-3 instruction blocks where they were presented with written instructions, and then practiced the dual task; they were only advanced to the main task after achieving an accuracy of at least 75% for the task, a stop-signal accuracy (percentage of stop-success given a stop signal appeared) of between 30% and 70%, and an average RT of less than 1000ms, or after they had completed three practice blocks. In all instructions, participants were encouraged to respond quickly without sacrificing accuracy. For practice and test trials, a stop signal would appear on 25% of the trials and the participants would attempt to withhold their response. The initial SSD in practice was 350 ms, and the SSD would then be titrated based on performance, where a successful inhibited response (i.e. no overt response) would increase the SSD by 50ms, and an unsuccessfully inhibited response would decrease the SSD by 50ms, with the full range of possible SSD values being 0-1000, inclusive. The practice-titrated SSD was carried over as the initial SSD for the test-trials. This 1-up/1-down tracking algorithm (Levitt, 1971) should yield a probability of responding given a stop signal of approximately .5. After each block, if their RT was above 1000ms, their accuracy was below 75%, or if they omitted their response on more than 10% of go trials, they were told they were responding too slowly, told that their accuracy was too low and reminded of the instructions, or told that they had not responded on too many trials and they needed to respond to all trials that required a response, respectively.

Analysis. In order to balance our goals of exploring the data (Thompson, Wright, & Bissett, 2020) while still allowing for confirmatory hypothesis testing, we randomly split the data half-wise ($n=33$ each) into a discovery set and a validation set. Any result was considered robust if it was present in both our initial exploration of the discovery dataset and the subsequent pre-registered confirmatory analysis in the validation dataset (<https://osf.io/g8qpd/>).

In order to examine the relationship among inhibition-related processes, we compared SSRT in a simple stop task and seven dual tasks. SSRT was calculated for the simple stop task as well as each task's dual context and dual condition trials separately (see Figure 1, Table

S11) using integration with replacement in accordance with Verbruggen et al. (2019).

Additionally, we computed several other metrics of stop-signal performance: mean SSD, mean $P(\text{respond}|\text{stop signal})$, the mean and standard deviation of RT on go trials and on stop-failure trials, the choice-accuracy on go trials and on stop-failure trials, go omission rate, and post-stop-slowing (PSS; the difference in response times of correct go trials that bookend a stop trial, subtracting pre from post, Bissett & Logan, 2011; Nelson, Boucher, Logan, Palmeri, & Schall, 2010).

Initially, we attempted to calculate the dual condition effect with Go/no-go, but these no-go + stop trials facilitated stopping and resulted in few or no failed inhibition (Mean $P(\text{respond})$ of no-go stop trials in the discovery set = 1.52%), so we could not compute an accurate estimate of SSRT (Verbruggen et al. 2019). Therefore, go/no-go was excluded from the following analyses. For each metric, subjects with scores greater than 3 standard deviations from the mean were removed.

The operationalization of dual context and dual condition (respectively) were as following for the six remaining tasks:

- predictable task switching: task stay and task switch
- cued task switching: task stay and task switch
- flanker: congruent and incongruent
- shape matching: distractor absent and distractor incongruent
- n-back: 1-back and 2-back
- directed forgetting: non-recent negative (probe was not in the original 4-stimulus memory set) and recent negative trials (probe was in the original 4-stimulus memory set but subjects were instructed to forget it).

Some recent work has shown evidence for violations of the context independence assumption, especially when SSDs are short (Bissett et al., 2021; Colonius et al., 2001; Gulberti et al., 2014). To check the robustness of our results against the potential impact of violations of

independence, we repeat our analyses using two distinct approaches: excluding short SSD trials (<200ms) or subjects with short SSDs (mean SSDs <200ms). We discuss the implication of these results for context independence violations in the Discussion. Code and data to replicate these results are available at <http://doi.org/10.5281/zenodo.5228416>.

Results

Discovery Dataset

In order to evaluate the relationship between inhibition-related processes we focused our analysis on the differences between SSRT in the simple stopping task with each dual context and dual condition effects in our dual task by computing differences scores between simple stop SSRT from dual context and dual condition SSRTs. These difference scores were used in a 6 (task: Predictable Task Switching, Cued Task Switching, Flanker, Shape Matching, N-Back, Directed Forgetting) by 2 (dual-type: dual context, dual condition) repeated-measures ANOVA on SSRT in order to investigate differentiable effects of concurrent control demands on inhibition. P-values were corrected for violations of sphericity using the Greenhouse-Geisser method (1959). If a subject's score was missing from one cell in the ANOVA, the subject would be fully removed from the ANOVA and not included in any follow-up pairwise comparisons. This criterion removed 2 subjects. This revealed a significant effect of task, $F(5,150)=28.1$, $MSE=3150$, $p < .001$, $\eta^2 = .37$, and of dual-type, $F(1,30) = 5.2$, $MSE=1549$, $p=.03$, $\eta^2 = .007$, with a bigger difference between dual and simple stop SSRT in dual condition compared to dual context. The task x dual-type Interaction was not significant, $F(5,150)=1.52$, $MSE=1443$, $p=.20$, $\eta^2 = .009$. Follow-up pairwise comparisons revealed that cued task switching, shape matching, n-back and directed forgetting had SSRTs significantly greater than simple stop, $t(30)$'s ≥ 2.9 , p 's $\leq .0066$ (Figure 1; Table S1). Taking the means across the 6 dual-tasks, SSRTs from both

dual types were significantly greater than SSRTs from the simple stop (dual context: $t(30)=4.45$, $p=0.001$; dual condition: $t(30)=5.06$, $p<.001$). Flanker and predictable task switching SSRTs were not significantly different from single task SSRTs (flanker: $t(30)=1.08$, $p=.29$; predictable task switching: $t=.67$, $p=.51$). The only task with significantly slower dual condition SSRT than dual context SSRT was the N-back, $t(30)=2.65$, $p=.013$ (all other p 's $\geq .32$). Hence, our putative working memory tasks had slower response inhibition than the simple stop task, and one of the two of each of our putative set shifting and selective attention tasks had slower response inhibition.

Figure 1. SSRT in Simple Stop and each of our six dual tasks, separated by dual trial type (dual context and dual condition). Error bars reflect the 95% confidence interval. Top: data from the Discovery Dataset. Bottom: data from the Validation Dataset.

Short SSDs have been shown to encourage violations of the context independence assumption of race models (Bissett et al., 2021), which can contaminate SSRT estimates. Post-hoc tests found significantly shorter mean SSDs in the directed forgetting dual task compared to the single task (Table S2), which was also the task with the largest slowing in SSRT. We evaluated violations using the methods in Bissett et al. (2021) which revealed some evidence for violations at short SSDs, especially in the directed forgetting task (Figure S1; see figure caption for a description of the methods). Therefore, in line with the suggestions from Bissett and colleagues (2021), SSRTs were recomputed while removing stop trials with SSDs < 200ms and removing subjects with a mean SSD < 200ms. When removing short SSD trials, all results were qualitatively the same (see Supplement for details; Tables S3), suggesting that our results were not contaminated by violations of context independence. Removing short SSD subjects (Table S4) eliminated 16 subjects. To more robustly evaluate the effects of removing short SSD subjects, we combined the 17 longer SSD subjects with the 11 longer SSD subjects from the validation sample (see Post Hoc Analyses on the Combined Dataset below; Table S13).

See the supplement for additional measures of stopping performance (Tables S5-S8) and analyses confirming that we replicated standard condition effects in the six tasks that were combined with the stop-signal task (e.g., the flanker effect, Tables S9-S10).

Validation Dataset

The discovery dataset analyses suggested that SSRTs are slowed in putative working memory tasks (n-back and directed forgetting), with some evidence of load dependence (n-back's 2-back SSRT > n-back's 1-back SSRT). The effects of other control demands were more variable: SSRT was impaired in shape matching but not in the flanker task, two putative measures of selective attention; and in cued task switching but not in predictable task switching, two putative measures of set shifting. Based upon these initial results, we preregistered a set of analyses to apply to the validation dataset with the prediction that the above results would

replicate (<https://osf.io/g8qpd/>). The same exclusion procedures described above were applied to these analyses.

To focus on the specific planned analyses in the validation sample, we preregistered a one-way repeated-measures ANOVA with 7 levels, one for each dual task along with the single task (<https://osf.io/g8qpd/>). For directed forgetting, n-back, cued task-switching, and shape matching, each task's difference in SSRTs from the simple stop task, meaned across each task's dual context and dual condition, was compared against 0 in a one-tailed test using the Mean Squared Error of the one-way ANOVA to estimate the standard error. In addition, the mean SSRT in the 2-back condition was compared against the mean SSRT in the 1-back condition using a one-tailed related-samples t-test to test whether higher N-back load had a specific influence on SSRT. Lastly, these analyses were repeated excluding trials with SSDs < 200ms, or subjects whose mean SSD was < 200ms.

In the full validation dataset, the one-way ANOVA revealed a significant effect of task, $F(6, 180)=34.75$, $MSE=1385$, $p<.001$, $\eta^2=.54$. Replicating the discovery dataset, planned contrasts revealed SSRTs were significantly slower in n-back, $t(180)=3.78$, $p<.001$, $d=.57$, directed forgetting, $t(180)=12.02$, $p<.001$, $d=1.84$, and shape matching, $t(180)=3.69$, $p<.001$, $p=1.01$. There was a trend towards slower SSRTs in cued task switching, $t(180)=1.624$, $p=.053$, $d=.30$, than SSRTs in the single task. Also replicating the discovery dataset, a one-tailed repeated-measures t-test found dual condition (2-back) SSRTs to be greater than dual context (1-back) SSRTs in n-back $t(30)=2.28$, $p=.015$, $d=.42$. Taken together, the validation analyses successfully replicated the main results from the discovery dataset, showing that response inhibition is slowed in the context of putative working memory tasks and variably impaired in the context of putative set shifting and selective attention tasks. The N-back task also showed larger SSRT slowing in the 2-back than the 1-back condition.

The results were qualitatively the same when excluding short SSD trials, except there was no longer a significant difference in SSRTs across n-back conditions, $t(25)=.255$, $p=.40$,

$d=.05$ (Table S12). Excluding subjects with mean SSDs $< 200\text{ms}$ results in excluding 22 subjects of the 33, leaving only 11; a major reduction in power. Therefore, we combined these 11 longer SSD subjects with the 17 longer SSD subjects from the discovery dataset.

Post-hoc Analysis on the Combined Dataset

Excluding subjects with mean SSDs $< 200\text{ms}$ resulted in the exclusion of 38 of our 66 subjects from our discovery and validation samples. Therefore, in order to increase our power to evaluate whether our results are robust to excluding subjects with predominantly violation-prone short SSDs (Bissett et al., 2021), we combined the longer SSD subjects from both datasets. This was a deviation from our pre-registration resulting from an unexpectedly large exclusion of short SSD subjects in the validation sample. After rerunning the preprocessing pipeline and exclusion criteria on the full dataset, 29 subjects remained (note, using both datasets resulted in a larger standard deviation of SSRT values for some conditions, which revealed one subject's SSRT in the flanker dual condition trial type to be no longer greater than 3 standard deviations from the mean and requalified that subject for analyses). All primary results replicated in this sample of 29 longer SSD subjects (Table S13). The one-way ANOVA revealed a significant main effect of task, $F(6, 168)=11.58$, $\text{MSE}=1439$, $p<.001$, $\eta^2=.29$. Applying the validation contrasts revealed SSRTs were significantly slower in n-back, $t(168)=3.03$, $p=.001$, $d=.54$, directed forgetting, $t(168)=7.08$, $p<.001$, $d=1.29$, shape matching, $t(168)=2.23$, $p=.013$, $d=.47$, and cued task switching, $t(168)=1.69$, $p=.046$, $d=.28$, than SSRTs in the single task. A one-tailed repeated-measures t-test found dual condition (2-back) SSRTs to be greater than dual context (1-back) SSRTs in n-back, $t(28)=2.38$, $p=.012$, $d=.45$.

Discussion

We used a dual-task approach to investigate the relationship between response inhibition and each of working memory, selective attention, and set shifting. For each of these control processes, we included two tasks in order to allow us to test whether any results generalize beyond the idiosyncrasies of a task to the corresponding putative cognitive construct. We also compared dual task performance to single task performance, allowing us to separate the effect of being in a dual task context (i.e., “dual context”) from the trial-level demands of engaging two inhibition-related processes (i.e., “dual condition”). We focused on SSRT as a measure of response inhibition and found that it was impaired when combined with the shape matching task but not the flanker task, and the cued (though note validation $p = .053$) but not predictable task switching task, suggesting that response inhibition is weakly or variably overlapping with selective attention and task switching, respectively. SSRT was impaired across both N-back and directed forgetting, consistent with an overlap in processing between response inhibition and working memory. Across tasks, SSRT impairments were primarily present when comparing even our easier dual context trials (e.g., flanker congruent trials) to a single-task SSRT (mean difference between dual context SSRTs and the single task SSRTs in the discovery and validation datasets were 31.7ms & 32.4ms, respectively), with comparatively less impairment when comparing the more difficult dual condition trial SSRT to easier dual task trial SSRT (mean difference between dual condition SSRTs and dual context SSRTs in the discovery and validation datasets were 9.3ms & 6.4ms, respectively). Hence, most of the SSRT impairment in dual tasks was also present even on the easier dual task trials, suggesting that response inhibition is primarily impaired by being in the context of a dual task and not due to the requirement to engage response inhibition and resolve the demands of another inhibition-related process on the same trial. Taken together, these results suggest that response inhibition processes are often impaired in the context of concurrent control demands, especially working

memory demands, even if those concurrent demands are not required on that specific trial. This suggests a taxonomy of control in which response inhibition overlaps with other related control processes, especially working memory.

Towards a Taxonomy of Cognitive Control Processes

Cognitive control is often understood as a set of acts of control (Logan, 1985), and given this framework, one key question is how these acts of control fit together. This manuscript extends and challenges an existing wealth of research on this topic. Our work challenges multiple existing lines of work that suggest that response inhibition and working memory-related processes are independent. First, Friedman and Miyake (2004), using confirmatory factor analysis, showed that prepotent response inhibition is unrelated to resisting proactive interference, a process related to working memory that should be necessary in our N-back and directed forgetting task. One possible explanation for this discrepancy involves different analytical approaches. Friedman and Miyake (2004) use an individual difference approach which is limited by the test-retest reliability of task measures, which are often low (Enkavi et al., 2019). Cognitive tasks are characterized by low between-subject variability, making them problematic for individual difference analyses but ideal for group comparisons, as we used here (Hedge, Powell, & Sumner, 2018). Second, Bissett et al. (2009) combined a directed forgetting task with a stop-signal task and showed that SSRT was similar on the difficult recent negative trials as on easier non-recent negative trials, which they took as evidence that working memory and response inhibition were distinct processes. Here, we show that SSRT is slowed when a stop signal is combined with an n-back or a directed forgetting task, two tasks that putatively involve working memory and resisting proactive interference. This result can be synthesized with Bissett and colleagues (2009) by recognizing our distinction between dual context and dual condition results. They did not investigate context-level SSRT impairment and only compared forget trials to control and positive trials, finding no difference. However, a closer examination

suggests that their directed forgetting SSRTs (see Bissett et al., 2009 Figure 2) were ~20ms slower than their control SSRTs in a context with lesser working memory demands (see BY trials in Bissett et al., 2009 Figure 4). Therefore, response inhibition appears to interact with working memory, but this interaction is driven by context-level overlap, a possibility that Bissett et al. (2009) did not investigate. Related, the N-back task was our only task to show a dual condition effect, but unlike the other tasks, which have various trial types intermixed within each block of trials, n-back's trial types (2-back vs. 1-back) were at the block level and therefore the prolonged SSRT on 2-back vs. 1-back can also be characterized as a context-level interaction between working memory and SSRT.

Our findings are more in line with research showing that working memory and response inhibition involve at least partially overlapping processes (Boucher et al., 2021; Chiu & Egner, 2015a; Chiu & Egner, 2015b). Boucher et al. (2021) showed that SSRT was prolonged in a high working memory load condition compared to a low working memory load condition. This mirrors our N-back results, which showed that SSRT was slower for the 2-back compared to the 1-back condition. There are working memory demands in all directed forgetting trials (initially four stimuli, of which two are then forgotten), which may explain why SSRT was prolonged on both directed forgetting trials and non-recent negative trials.

Our dual tasks involving task switching resulted in mixed results, with SSRT impairments in cued task switching but not predictable task switching. Verbruggen et al. (2005) found no SSRT impairment in cued task switching for task switch vs. task stay trials. Mirroring the above discussion of the Bissett et al. (2009) results, Verbruggen et al. (2005) only focused on trial-level results (task stay vs. task switch). Our null effect comparing SSRT on task switch versus task stay trials replicates Verbruggen et al. (2005), but we show that being in the context of a cued task switching task (though note the $p = .053$ of the validation sample) but not a predictable task switching task slows SSRT. The fully-predictable task order in our predictable task switching task may have allowed participants to front load task-set updating in a way that reduces overlap

with inhibition processes, reducing the interference between control demands, relative to that seen in our cued task switching task, where such front loading would not be possible due to a lack of predictable structure.

Finally, we found context-level SSRT slowing in the shape matching task but not the flanker task. Kramer et al. (1994), Ridderinkhof et al. (1999), and Verbruggen et al. (2004) showed that SSRT increased on incongruent flanker trials compared to congruent flanker trials, which we did not replicate, but we did find SSRT increases in the shape matching task compared to the simple stop task. Our finding of SSRT slowing in shape matching but not flanker could be explained by specific aspects of the shape matching task including higher attentional challenge/load (when the distractor appeared it overlapped with the probe, requiring even more spatially specific attention generally), split attention (i.e. subjects had to focus on both the probe and target), or by a difference in the final decision process (subjects had to identify both probe and target in order to make a same-different judgement, compared to a single identification in the flanker task). Each of these dimensions could be manipulated in future investigations.

On Process Impurity and Working Memory as a Proposed Mechanism underlying SSRT Slowing

Cognitive tasks suffer from the “process impurity” problem, which suggests that any task will measure a conglomeration of multiple constituent processes (Jacoby, 1991; Sorqvist et al., 2010). We labeled each of our eight tasks with a putative cognitive construct that we believe aligns to the dominant assignment in the literature, but we do not mean to suggest that this is the only process that this task captures. Further, specific work has questioned the putative link between some of our tasks and their putative dominant construct, including questioning whether the N-back task captures working memory (Kane, Conway, Miura, & Colflesh, 2007), the necessity of response inhibition to model the go/no-go task (Gomez, Ratcliff, & Perea, 2007),

and whether task switching requires an endogenous act of control (like set shifting) to switch tasks (Logan & Bundesen, 2003). Therefore, the mapping between task and construct is neither one-to-one nor firmly established in all cases.

In this vein, in order to attempt to synthesize these apparently mixed results, we suggest that the relationship between response inhibition and working memory may be able to parsimoniously explain all of our results. Specifically, we propose that SSRT increases with working memory demands, and there may be differential working memory demands across our tasks, even those not intended to directly capture the construct of working memory. Directed forgetting involves holding four items in mind and manipulating them, putting perhaps the largest demand on working memory of all of our tasks, and also results in the largest and most consistent SSRT slowing. The N-back task, which involves holding and frequently updating one or more stimuli, also resulted in consistent SSRT slowing, especially in the more demanding 2-back condition. We also tended to observe SSRT slowing in the cued task switching task, which also involves remembering a complicated four-cue-to-two-task mapping and remembering the cue during an interval, which may put demands on working memory. SSRT was also slowed in the shape matching task, which may involve working memory demands including extracting a filtered probe into working memory (i.e., a representation of the probe that excludes the superposition of the distractor from the environment) to compare to the target and may involve purging the distractor from working memory. Conversely, the flanker task and predictable task switching tasks did not show SSRT slowing and may involve minimal working memory demands. The flanker task involves filtering attention distraction and a straightforward mapping of the letters F and H onto the F and H keys, so does not have significant apparent working memory demands. Also, as mentioned in the previous section, the predictable task switching task may have allowed participants to preemptively update their task set before the probe occurs, which may reduce or eliminate working memory demands during the trial. We prefer this working memory hypothesis to a more general hypothesis that SSRT increases with the

difficulty of the secondary task because dual-task SSRTs did not scale with RT or accuracy of the dual task (see Tables S6 and S8 for t-tests comparing RTs and accuracies, respectively, and Table S11 for descriptive summary metrics across the tasks).

This interaction between inhibition and working memory may arise due to overlapping neural circuitry. Working memory is frequently conceptualized as a buffer with two main processes: maintenance of its contents, and selective updating of its contents. Some modern theories of working memory (e.g. the Prefrontal Cortex Basal Ganglia Working Memory Model; O'Reilly & Frank, 2006) posit that motor control circuits of the basal ganglia are exapted in order to support working memory updating. Similar basal ganglia circuitry has also been proposed to underlie motor execution and response inhibition (Aron & Poldrack, 2006; Hannah & Aron, 2021; Mink, 1996). Therefore, overlapping basal ganglia circuitry may result in an overlap in processing between working memory updating and response inhibition, slowing SSRT. Additionally, the tasks with prolonged SSRT (directed forgetting, n-back, cued task switching, and shape matching) seem to not only involve additional working memory demands generally, as discussed in the immediately preceding paragraph, but also additional specific demands on updating, consistent with this theory. There is also compelling evidence that implicates cerebellar circuitry with working memory updating (McDougal et al., 2021) and response inhibition (Hirose et al., 2014), suggesting that interactions between higher-order processes may require coordinated activity across the central nervous system (Shine, 2021).

We view this hypothesis as preliminary until evaluated with more rigorous scrutiny including more systematic manipulation of working memory demands across multiple dual tasks that include response inhibition. This hypothesis suggests that apparent links between set shifting and response inhibition as well as selective attention and response inhibition may be because certain tasks that putatively capture set shifting and selective attention also involve working memory, with the fundamental overlap in processes being between working memory

and response inhibition and not between selective attention and response inhibition or set shifting and response inhibition.

Dependence between Stopping and Going

This work builds on a wealth of evidence that shows response inhibition is not immutable and instead changes under various conditions (e.g., Bissett et al., 2021; Kramer et al., 1994; Verbruggen et al., 2004). We found that SSRT was prolonged when combined with a working memory task, and we found that SSRT was sometimes prolonged when combined with putative set shifting and selective attention tasks. In the beginning of this manuscript, we likened the stop-signal task to driving a car, where one must be prepared for an unlikely requirement to stop a motor response. Driving also involves working memory demands (e.g., directions to make a left, go 4 blocks, make a right, then turn into the third driveway on the right), selective attention (attend to signs and pedestrians while ignoring billboards), and task switching (e.g., going to and from adjusting a radio station). Our results suggest that the presence of these secondary tasks, especially working memory demands, slow SSRT. Therefore, when speeded response inhibition is necessary, it is important to consider concurrent control demands, as there is functional dependence between control processes that influence going (especially working memory demands) and response inhibition.

These interactions relate to recent work that challenges the fundamental assumption of context independence between going and stopping (Bissett et al., 2021) that is the foundation of the Independent Race Model (Logan & Cowan, 1984). Bissett and colleagues (2021) show that the go process is impaired by the presence of the stop signal, especially at short SSDs, revealing violations of context independence. Short SSDs are rare in our data, so context independence violations were also rare (though see Figure S1), but our results relate to Bissett and colleagues (2021) in showing that the stop process is not independent from the demands of

the go task, and will be impaired if SSD is short, when working memory demands are high, and perhaps if task switching and selective attention demands are high. However, though the functional dependence observed in this manuscript shares some relation to the context dependence shown previously (e.g., Bissett et al., 2021), as we discuss in the introduction, functional dependence does not violate the assumptions of the Independent Race Model for the stop-signal task but context dependence does.

A Case Study on Avoiding Violations of Context Independence

Given recent work showing violations of context independence that are most severe at short SSDs (Bissett et al., 2021), and that such violations contaminate SSRT estimates, we took two proactive and two reactive steps to avoid and account for such violations. The first two were proactive strategies implemented during experimental design. First, we complicated the go process by adding additional demands, slowing RT in most of our tasks, which in concert with our 1-up/1-down SSD tracking algorithm (Levitt, 1971), attempted to avoid short SSDs. This strategy was largely successful, as only 9% of trials had SSDs < 200ms compared to 40% in a recent sample of 14 datasets (Bissett et al., 2021). Second, we used simple stopping instead of the more violation-prone selective stopping (Bissett & Logan, 2014; Bissett et al., 2021). The last two strategies to avoid violations were more reactive and were implemented during data analysis. Third, we evaluated whether our results were similar when short SSDs (<200ms) were removed. Fourth, we evaluated whether our results were similar when subjects with predominantly short SSDs (mean <200ms) were removed. Our proactive strategies worked to avoid short SSDs, and our reactive strategies showed that our results were robust when removing the remaining violation-prone short SSDs trials and subjects.

Conclusion

We used a dual-task approach to understand the relationship between different inhibition-related processes. We designed the study to allow us to separately capture impairment from being in a dual task context from the traditional measure of impairment when resolving two inhibition-related demands on a given trial. We found that response inhibition impairments were primarily driven by context-level and not trial-level effects. Response inhibition was impaired when working memory demands were high and also was variably impaired when task switching and selective attention demands increased. These results suggest that response inhibition processes are often impaired in the context of concurrent control demands, especially working memory demands, even if those concurrent demands are not required on that specific trial. This suggests a taxonomy of control in which response inhibition overlaps with other inhibition-related processes, especially working memory.

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Supplement

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) vs. Single Task	Predictable Task Switching	6.0	0.12	0.506
	Cued Task Switching	29.8	0.52	0.007
	Flanker	6.9	0.19	0.291
	Shape Matching	28.6	0.58	0.003
	n-Back	37.7	0.74	0.000
	Directed Forgetting	108.9	1.42	0.000
	All	31.7	0.80	0.000
Dual Context vs. Single Task	Predictable Task Switching	2.3	0.04	0.823
	Cued Task Switching	26.5	0.41	0.030
	Flanker	6.8	0.17	0.351
	Shape Matching	27.6	0.56	0.004
	n-Back	21.2	0.43	0.022
	Directed Forgetting	105.6	1.25	0.000
	All	41.0	0.91	0.000
Dual Condition vs. Single Task	Predictable Task Switching	9.8	0.19	0.305
	Cued Task Switching	33.2	0.54	0.005
	Flanker	6.9	0.17	0.356
	Shape Matching	29.5	0.55	0.005
	n-Back	54.2	0.76	0.000
	Directed Forgetting	112.1	1.30	0.000
	All	9.3	0.41	0.030
Dual Condition vs. Dual Context	Predictable Task Switching	7.5	0.18	0.321
	Cued Task Switching	6.7	0.13	0.491
	Flanker	0.1	0.00	0.987
	Shape Matching	1.9	0.06	0.738
	n-Back	32.9	0.48	0.013
	Directed Forgetting	6.5	0.09	0.635
	All			

Table S1. Post-hoc t-tests on the difference in SSRTs in the discovery dataset. Tests were run to determine if each dual-task's SSRT (meaned across the 2 conditions) was different from SSRTs in the single task, if SSRTs from the easier dual context or the harder dual condition trial types were different from SSRTs in the single task, and finally if SSRTs in the dual condition trial types were different from SSRTs in the single task. The 'mean' column indicates the mean difference in SSRTs. d is Cohen's d.

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) vs. Single Task	Predictable Task Switching	41.4	0.30	0.106
	Cued Task Switching	54.1	0.35	0.061
	Flanker	-42.9	-0.28	0.134
	Shape Matching	-7.6	-0.05	0.779
	n-Back	10.1	0.07	0.718
	Directed Forgetting	-167.9	-1.03	0.000
	All	-23.4	-0.18	0.337
Dual Context vs. Single Task	Predictable Task Switching	27.2	0.20	0.285
	Cued Task Switching	47.4	0.31	0.094
	Flanker	-54.4	-0.35	0.059
	Shape Matching	-23.0	-0.15	0.406
	n-Back	29.1	0.17	0.344
	Directed Forgetting	-166.7	-1.01	0.000
	All	-14.2	-0.11	0.555
Dual Condition vs. Single Task	Predictable Task Switching	55.6	0.40	0.036
	Cued Task Switching	60.8	0.38	0.040
	Flanker	-31.3	-0.20	0.275
	Shape Matching	7.9	0.05	0.767
	n-Back	-8.9	-0.06	0.744
	Directed Forgetting	-169.0	-1.04	0.000
	All	9.2	0.53	0.006
Dual Condition vs. Dual Context	Predictable Task Switching	28.4	0.66	0.001
	Cued Task Switching	13.4	0.42	0.025
	Flanker	23.1	0.83	0.000
	Shape Matching	30.9	0.93	0.000
	n-Back	-38.0	-0.46	0.015
	Directed Forgetting	-2.3	-0.10	0.578
	All			

Table S2. Post-hoc t-tests comparing the mean sampled SSD in the dual trial types against the single task in the discovery dataset.

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) vs. Single Task	Predictable Task Switching	2.1	0.04	0.833
	Cued Task Switching	23.2	0.40	0.050
	Flanker	2.6	0.07	0.717
	Shape Matching	21.3	0.43	0.037
	n-Back	36.0	0.70	0.002
	Directed Forgetting	37.0	0.58	0.006
	All	13.3	0.36	0.075
Dual Context vs. Single Task	Predictable Task Switching	-2.8	-0.05	0.807
	Cued Task Switching	16.3	0.26	0.189
	Flanker	3.0	0.07	0.711
	Shape Matching	18.5	0.38	0.063
	n-Back	16.4	0.32	0.116
	Directed Forgetting	28.4	0.37	0.071
	All	27.4	0.65	0.003
Dual Condition vs. Single Task	Predictable Task Switching	7.0	0.14	0.476
	Cued Task Switching	30.1	0.46	0.026
	Flanker	2.1	0.05	0.793
	Shape Matching	24.2	0.44	0.035
	n-Back	55.6	0.78	0.001
	Directed Forgetting	45.5	0.60	0.005
	All	14.1	0.60	0.005
Dual Condition vs. Dual Context	Predictable Task Switching	9.7	0.29	0.157
	Cued Task Switching	13.8	0.26	0.199
	Flanker	-0.9	-0.02	0.911
	Shape Matching	5.7	0.17	0.387
	n-Back	39.2	0.57	0.008
	Directed Forgetting	17.2	0.20	0.309
	All			

Table S3. Post-hoc t-tests on the difference in SSRTs in the discovery dataset while excluding short SSD trials (SSD < 200ms).

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) vs. Single Task	Predictable Task Switching	-7.5	-0.15	0.551
	Cued Task Switching	21.8	0.33	0.194
	Flanker	-0.8	-0.02	0.939
	Shape Matching	11.4	0.21	0.394
	n-Back	32.1	0.55	0.039
	Directed Forgetting	61.5	1.03	0.001
Dual Context vs. Single Task	All	15.5	0.38	0.141
	Predictable Task Switching	-11.8	-0.20	0.417
	Cued Task Switching	21.7	0.32	0.201
	Flanker	4.8	0.09	0.701
	Shape Matching	9.9	0.18	0.467
	n-Back	15.9	0.29	0.249
Dual Condition vs. Single Task	Directed Forgetting	52.7	0.81	0.004
	All	24.0	0.49	0.059
	Predictable Task Switching	-3.2	-0.06	0.795
	Cued Task Switching	21.9	0.29	0.251
	Flanker	-6.4	-0.16	0.528
	Shape Matching	12.8	0.22	0.368
Dual Condition vs. Dual Context	n-Back	48.3	0.61	0.024
	Directed Forgetting	70.3	0.88	0.002
	All	8.4	0.35	0.171
	Predictable Task Switching	8.7	0.23	0.351
	Cued Task Switching	0.2	0.00	0.989
	Flanker	-11.1	-0.29	0.250
	Shape Matching	3.0	0.09	0.713
	n-Back	32.4	0.46	0.074
	Directed Forgetting	17.6	0.21	0.404

Table S4. Post-hoc t-tests on the difference in SSRTs in the discovery dataset while excluding short SSD subjects (mean SSD < 200ms).

		Mean	d	p
	Test	Dual Task(s)		
mean(Dual Context, Dual Condition) vs. Single Task	Predictable Task Switching	0.003	0.08	0.657
	Cued Task Switching	0.007	0.11	0.541
	Flanker	-0.005	-0.14	0.440
	Shape Matching	0.002	0.05	0.774
	n-Back	-0.016	-0.42	0.025
	Directed Forgetting	0.051	0.48	0.012
	All	0.016	0.39	0.036
	Predictable Task Switching	0.006	0.16	0.374
	Cued Task Switching	0.014	0.15	0.411
	Flanker	-0.001	-0.02	0.895
	Shape Matching	-0.001	-0.03	0.878
	n-Back	0.003	0.04	0.814
	Directed Forgetting	0.072	0.55	0.004
	All	-0.002	-0.05	0.798
	Predictable Task Switching	-0.000	-0.00	0.986
Dual Context vs. Single Task	Cued Task Switching	-0.001	-0.02	0.909
	Flanker	-0.009	-0.23	0.201
	Shape Matching	0.004	0.13	0.487
	n-Back	-0.034	-0.75	0.000
	Directed Forgetting	0.029	0.18	0.332
	All	-0.017	-0.40	0.033
	Predictable Task Switching	-0.006	-0.22	0.234
Dual Condition vs. Single Task	Cued Task Switching	-0.015	-0.17	0.347
	Flanker	-0.008	-0.25	0.178
	Shape Matching	0.005	0.21	0.257
	n-Back	-0.036	-0.47	0.013
	Directed Forgetting	-0.044	-0.21	0.251
	All	-0.017	-0.40	0.033
	Predictable Task Switching	-0.006	-0.22	0.234
Dual Condition vs. Dual Context	Cued Task Switching	-0.015	-0.17	0.347
	Flanker	-0.008	-0.25	0.178
	Shape Matching	0.005	0.21	0.257
	n-Back	-0.036	-0.47	0.013
	Directed Forgetting	-0.044	-0.21	0.251
	All	-0.017	-0.40	0.033
	Predictable Task Switching	-0.006	-0.22	0.234

Table S5. Post-hoc tests of commission error rates on stop-failure trials in dual task trial types compared to the single task in the discovery dataset.

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) vs. Single Task	Predictable Task Switching	67.2	0.47	0.013
	Cued Task Switching	97.3	0.67	0.001
	Flanker	-25.6	-0.17	0.332
	Shape Matching	35.8	0.25	0.164
	n-Back	63.2	0.44	0.018
	Directed Forgetting	-49.3	-0.33	0.069
	All	19.0	0.15	0.407
Dual Context vs. Single Task	Predictable Task Switching	45.7	0.32	0.083
	Cued Task Switching	86.0	0.57	0.003
	Flanker	-35.8	-0.24	0.182
	Shape Matching	21.9	0.15	0.393
	n-Back	55.9	0.37	0.047
	Directed Forgetting	-59.6	-0.41	0.029
	All	43.9	0.35	0.059
Dual Condition vs. Single Task	Predictable Task Switching	88.8	0.60	0.002
	Cued Task Switching	108.6	0.76	0.000
	Flanker	-15.5	-0.11	0.554
	Shape Matching	49.7	0.35	0.058
	n-Back	70.6	0.50	0.008
	Directed Forgetting	-39.0	-0.26	0.153
	All	24.9	1.18	0.000
Dual Condition vs. Dual Context	Predictable Task Switching	43.1	0.92	0.000
	Cued Task Switching	22.6	0.58	0.003
	Flanker	20.4	0.99	0.000
	Shape Matching	27.8	0.98	0.000
	n-Back	14.7	0.25	0.163
	Directed Forgetting	20.5	0.63	0.001
	All	24.9	1.18	0.000

Table S6. Post-hoc tests of mean reaction time on go trials in dual task conditions compared to the single task in the discovery dataset.

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) vs. Single Task	Predictable Task Switching	31.0	0.63	0.002
	Cued Task Switching	22.6	0.59	0.003
	Flanker	-0.0	-0.00	0.996
	Shape Matching	1.8	0.04	0.828
	n-Back	51.0	0.88	0.000
	Directed Forgetting	26.5	0.54	0.006
	All	16.6	0.41	0.032
	Predictable Task Switching	19.6	0.44	0.024
	Cued Task Switching	22.6	0.54	0.006
	Flanker	1.8	0.04	0.815
	Shape Matching	-0.1	-0.00	0.987
	n-Back	39.9	0.59	0.003
	Directed Forgetting	15.7	0.28	0.133
	All	27.7	0.71	0.001
Dual Context vs. Single Task	Predictable Task Switching	42.4	0.73	0.000
	Cued Task Switching	22.6	0.56	0.005
	Flanker	-1.9	-0.05	0.800
	Shape Matching	3.7	0.09	0.641
	n-Back	62.1	1.06	0.000
	Directed Forgetting	37.4	0.72	0.000
	All	11.1	0.76	0.000
Dual Condition vs. Single Task	Predictable Task Switching	22.8	0.65	0.001
	Cued Task Switching	-0.0	-0.00	1.000
	Flanker	-3.8	-0.18	0.338
	Shape Matching	3.8	0.15	0.433
	n-Back	22.1	0.42	0.029
	Directed Forgetting	21.7	0.48	0.014
	All	11.1	0.76	0.000
Dual Condition vs. Dual Context	Predictable Task Switching	22.8	0.65	0.001
	Cued Task Switching	-0.0	-0.00	1.000
	Flanker	-3.8	-0.18	0.338
	Shape Matching	3.8	0.15	0.433
	n-Back	22.1	0.42	0.029
	Directed Forgetting	21.7	0.48	0.014
	All	11.1	0.76	0.000

Table S7. Post-hoc tests of standard deviation of reaction times on go trials in dual task conditions compared to the single task in the discovery dataset.

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) vs. Single Task	Predictable Task Switching	-0.091	-2.26	0.000
	Cued Task Switching	-0.083	-1.58	0.000
	Flanker	-0.003	-0.18	0.336
	Shape Matching	-0.019	-0.58	0.004
	n-Back	-0.127	-2.31	0.000
	Directed Forgetting	-0.049	-1.74	0.000
	All	-0.041	-1.72	0.000
	Predictable Task Switching	-0.071	-1.64	0.000
	Cued Task Switching	-0.068	-1.29	0.000
	Flanker	0.001	0.07	0.698
	Shape Matching	-0.013	-0.43	0.027
	n-Back	-0.073	-0.90	0.000
	Directed Forgetting	-0.020	-0.70	0.001
	All	-0.083	-2.74	0.000
Dual Context vs. Single Task	Predictable Task Switching	-0.111	-2.24	0.000
	Cued Task Switching	-0.097	-1.57	0.000
	Flanker	-0.007	-0.40	0.038
	Shape Matching	-0.025	-0.57	0.004
	n-Back	-0.182	-2.45	0.000
	Directed Forgetting	-0.079	-1.47	0.000
	All	-0.043	-1.62	0.000
Dual Condition vs. Single Task	Predictable Task Switching	-0.039	-0.84	0.000
	Cued Task Switching	-0.029	-0.61	0.002
	Flanker	-0.008	-0.59	0.003
	Shape Matching	-0.012	-0.33	0.085
	n-Back	-0.108	-1.00	0.000
	Directed Forgetting	-0.058	-0.90	0.000
	All	-0.043	-1.62	0.000
Dual Condition vs. Dual Context	Predictable Task Switching	-0.039	-0.84	0.000
	Cued Task Switching	-0.029	-0.61	0.002
	Flanker	-0.008	-0.59	0.003
	Shape Matching	-0.012	-0.33	0.085
	n-Back	-0.108	-1.00	0.000
	Directed Forgetting	-0.058	-0.90	0.000
	All	-0.043	-1.62	0.000

Table S8. Post-hoc tests of choice accuracy on go trials in dual task conditions compared to the single task in the discovery dataset.

Task		Contrast	Mean	d	p
Flanker		incongruent - congruent	21.7	0.98	0.000
Cued Task Switching	cue switch task stay - cue stay task stay		21.8	0.49	0.008
Cued Task Switching	cue switch task switch - cue stay task stay		23.1	0.60	0.002
Cued Task Switching	task switch - cue switch		1.2	0.04	0.822
Predictable Task Switching	switch - stay		41.5	0.92	0.000
Directed Forgetting	neg - con		22.5	0.65	0.001
Shape Matching	distractor - control		28.6	0.94	0.000
n-Back	2 - 1		13.5	0.22	0.207
n-Back	3 - 1		17.1	0.28	0.121

Table S9. Simple task contrasts comparing changes in response time between conditions within the dual tasks in the discovery dataset.

Task		Contrast	Mean	d	p
Flanker		incongruent - congruent	-0.017	-0.40	0.027
Cued Task Switching		cue switch task stay - cue stay task stay	-0.006	-0.10	0.578
Cued Task Switching		cue switch task switch - cue stay task stay	-0.028	-0.61	0.001
Cued Task Switching		task switch - cue switch	-0.022	-0.38	0.036
Predictable Task Switching		switch - stay	-0.043	-0.85	0.000
Directed Forgetting		neg - con	-0.054	-0.81	0.000
Shape Matching		distractor - control	-0.013	-0.35	0.053
n-Back		2 - 1	-0.102	-0.94	0.000
n-Back		3 - 1	-0.184	-1.50	0.000

Table S10. Simple task contrasts comparing changes in choice accuracy of go trials between conditions within the dual tasks in the discovery dataset.

Task	Condition	SSRT	mean SSD	p_respond	mean_go_RT	sd_go_RT	mean_stopfail_RT	sd_stopfail_RT	omission_rate	go_acc	stopfail_acc	PSS_all
Single Task		234.2	416.7	0.49	659.1	115.3	588.0	87.3	0.003	0.99	0.994	0.56
Cued Task Switching	cue_stay_task_stay	263.7	467.6	0.51	747.7	140.3	668.5	107.6	0.024	0.92	0.956	1.34
Cued Task Switching	cue_switch_task_switch	269.5	481.2	0.49	771.0	140.9	695.6	108.8	0.022	0.90	0.927	2.49
Cued Task Switching	[cue_switch_task_stay]	263.2	472.0	0.45	771.7	144.2	686.7	94.5	0.017	0.92	0.956	28.72
Directed Forgetting	con	336.5	263.9	0.56	606.0	133.1	562.5	109.7	0.010	0.97	0.967	-2.76
Directed Forgetting	neg	340.0	260.8	0.51	625.1	155.1	566.1	113.9	0.009	0.91	0.919	4.76
Directed Forgetting	[pos]	305.8	265.6	0.56	563.0	145.0	526.3	135.7	0.005	0.90	0.846	-3.12
Flanker	congruent	237.8	363.7	0.49	626.2	119.8	562.1	85.8	0.006	0.99	0.991	6.55
Flanker	incongruent	238.5	388.0	0.48	647.0	117.0	592.6	91.8	0.007	0.98	0.975	4.29
n-Back	1.0	256.8	444.6	0.49	715.8	156.2	641.6	113.0	0.010	0.91	0.915	16.77
n-Back	2.0	295.3	404.6	0.46	734.4	179.6	641.2	156.7	0.006	0.80	0.868	-5.69
n-Back	[3.0]	277.4	427.7	0.46	740.1	177.5	630.1	147.2	0.019	0.72	0.733	6.07
Predictable Task Switching	stay	238.6	457.0	0.50	704.7	141.0	628.2	98.2	0.010	0.92	0.934	-0.76
Predictable Task Switching	switch	248.5	483.6	0.49	757.9	161.7	655.4	124.6	0.008	0.88	0.913	21.72
Shape Matching	control	268.3	390.8	0.49	682.3	117.4	632.1	100.6	0.002	0.97	0.977	0.25
Shape Matching	distractor	269.4	419.9	0.49	709.4	123.3	655.8	103.7	0.004	0.96	0.967	7.64
Shape Matching	[DSD, SSS]	264.7	412.9	0.49	696.8	119.6	642.1	102.6	0.006	0.98	0.984	13.76

Table S11. The mean value for each dual task condition of various common metrics collected on the stop-signal task. Conditions in brackets were excluded from the dual context and dual condition analyses; see the main text for discussion. Data shown is from the discovery dataset.

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) > Single Task	Cued Task Switching	15.7	0.28	0.056
	Shape Matching	34.9	0.91	0.000
	n-Back	25.5	0.41	0.005
	Directed Forgetting	37.1	0.62	0.000
Dual Condition > Dual Context	n-Back	5.1	0.05	0.400

Table S12. Planned tests of differences in SSRTs applied to the validation dataset while excluding short SSD Trials (SSD < 200ms).

		Mean	d	p
Test	Dual Task(s)			
mean(Dual Context, Dual Condition) > Single Task	Cued Task Switching	16.8	0.28	0.007
	Shape Matching	22.3	0.47	0.001
	n-Back	30.2	0.54	0.000
	Directed Forgetting	70.6	1.29	0.000
Dual Condition > Dual Context	n-Back	33.3	0.45	0.012

Table S13. post-hoc tests of differences in SSRTs while excluding short SSD subjects (mean SSD < 200ms), applied to the fully combined dataset.

Figure S1. Violations of context independence across the 7 tasks using the methods of Bissett et al. 2021. Briefly, for each subject in each task, the response time of correct go trials that immediately precede stop-failure trials were subtracted from the stop-failure response times, and indexed by the stop trial's SSD. Positive values indicate that the go process of the stop-failure trial is prolonged (Bissett et al., 2021), violating the context independence assumption of the independent race model (Logan & Cowan, 1984). Within a task, a subject's mean violation was included if they experienced at least 2 stop-failure-preceded-by-correct-go trial pairs at that SSD. Also within a task, the data for a given SSD was kept if at least 5 subjects were included. There is some evidence for violations at shorter SSDs (positive values), especially in directed forgetting and N-back tasks. The gray band around the mean is the 95% confidence interval of the linear mixed effect model using data from all conditions.