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A unified account of simple and response-selective inhibition

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Abbreviated title: SELECTIVE STOPPING

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Code/Data Accessibility: All code and data are available from <https://osf.io/5z9vk/>

Abstract

1
2 Response inhibition is a key attribute of human executive control. Standard
3 stop-signal tasks require countermanding a single response; the speed at which that
4 response can be inhibited indexes the efficacy of the inhibitory control networks. However,
5 more complex stopping tasks, where one or more components of a multi-component action
6 are cancelled (i.e., response-selective stopping) cannot be explained by the
7 independent-race model appropriate for the simple task (Logan and Cowan 1984). Healthy
8 human participants ($n = 28$; 10 male; 19–40 years) completed a response-selective stopping
9 task where a ‘go’ stimulus required simultaneous (bimanual) button presses in response to
10 left and right pointing green arrows. On a subset of trials (30%) one, or both, arrows
11 turned red (constituting the stop signal) requiring that only the button-press(es) associated
12 with red arrows be cancelled. Electromyographic recordings from both index fingers (first
13 dorsal interosseous) permitted the assessment of both voluntary motor responses that
14 resulted in overt button presses, and activity that was cancelled prior to an overt response
15 (i.e., partial, or covert, responses). We propose a simultaneously inhibit and start (SIS)
16 model that extends the independent race model and provides a highly accurate account of
17 response-selective stopping data. Together with fine-grained EMG analysis, our
18 model-based analysis offers converging evidence that the selective-stop signal
19 simultaneously triggers a process that stops the bimanual response and triggers a new
20 unimanual response corresponding to the green arrow. Our results require a
21 reconceptualization of response-selective stopping and offer a tractable framework for
22 assessing such tasks in healthy and patient populations.

Significance Statement

23
24 Response inhibition is a key attribute of human executive control, frequently
25 investigated using the stop-signal task. After initiating a motor response to a go signal, a
26 stop signal occasionally appears at a delay, requiring cancellation of the response. This has

27 been conceptualised as a ‘race’ between the go and stop processes, with the successful (or
28 failed) cancellation determined by which process wins the race. Here we provide a novel
29 computational model for a complex variation of the stop-signal task, where only one
30 component of a multicomponent action needs to be cancelled. We provide compelling
31 muscle activation data that support our model, providing a robust and plausible framework
32 for studying these complex inhibition tasks in both healthy and pathological cohorts.

Introduction

33

34 Response inhibition is a key feature of executive function most commonly assessed
35 using the stop-signal task (Verbruggen et al., 2019). The standard stop-signal task requires
36 rapid choice responses (e.g., a left or right button press) to a “go” stimulus (e.g., a left or
37 right pointing arrow), that on some trials must be canceled when a second stimulus occurs
38 some time later (the stop-signal delay, SSD; Table 1 lists the acronyms used in this article).
39 Assuming a simple independent race between processes or “runners” with variable speeds
40 triggered by the go and stop signals (Logan & Cowan, 1984), the standard task affords a
41 key index of executive control, the running time of the inhibitory process. Go response
42 time (RT) is much slower than the running time of the inhibitory process, which is called
43 stop-signal reaction time (SSRT), consistent with stopping being mediated by a
44 specialized fronto-basal ganglia network (Sebastian, Forstmann, & Matzke, 2018).

45 Although the standard task is widely used (Matzke, Verbruggen, & Logan, 2018),
46 more complex response-selective inhibition tasks—where only some components of a
47 multi-component action are cancelled, with the remaining components being executed as
48 quickly as possible—may be more relevant to inhibition in the real-world (Aron &
49 Verbruggen, 2008), and to executive-function disorders (Aron, 2011). A common example
50 occurs when initiating a manual gear change, braking with one foot and pressing the clutch
51 with the other. When a dangerous change in road conditions occurs, clutching is aborted
52 while still braking. In the laboratory analogue, participants simultaneously press a button
53 with each hand in response to the go signal (e.g., a pair of left and right pointing green
54 arrows). If a selective stop signal occurs (e.g., one arrow turns red) the corresponding
55 button press is withheld but the other still made.

56 Here we show that the traditional explanation of selective stopping, as instantiated in
57 the Activation-Threshold Model (ATM, see Figure 1A: MacDonald, Coxon, Stinear, &
58 Byblow, 2014; MacDonald, McMorland, Stinear, Coxon, & Byblow, 2017), is inconsistent
59 with electromyographic (EMG) activity in a task mixing two types of stopping trials,

60 selective stopping and standard stopping (i.e., both arrows turn red and no response should
 61 be produced). We then propose a new model, called simultaneously inhibit and start (SIS,
 62 see Figure 1B), which provides a unified explanation of both standard selective stopping
 63 trials as well go trials (i.e., trials with no stop signal). We show that SIS accurately
 64 characterizes both EMG and all aspects of behavior, including the probability of stopping
 65 and the full distribution of RT in any case where responses do occur.

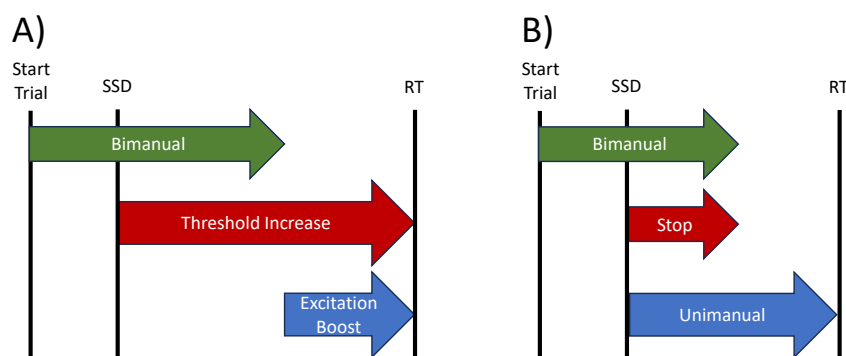


Figure 1. Models of a successful selective-stop trial. A) The Activation-Threshold Model (ATM): Presentation of go stimulus starts a unitary bimanual-response production process (green arrow), then at a time SSD later, before the bimanual process has reached the response thresholds a selective stop signal causes a threshold increase (red arrow), and after a further delay an excitation boost is added to response activation (blue arrow) so that eventually the threshold is reached at time RT and a unimanual response is produced. B) The simultaneous inhibit and start (SIS) model: Presentation of go stimulus starts a unitary bimanual-response runner (green arrow), then at SSD the stop signal triggers both a stop runner (red arrow) and a unimanual response runner. The stop runner catches and inhibits the bimanual runner and some time later the unimanual runner triggers a corresponding response

66 The traditional approach assumes a global inhibitory process is triggered by both
 67 standard and selective stop trials, with a subsequent “restart” process required to produce

Table 1

Acronyms and their meanings.

Type	Acronym	Meaning
Stimulus	DS	dual stimulus (no following stimuli)
	SS	stop stimulus (DS followed by bimanual stop signal)
	LS	left stimulus (DS followed by unimanual stop-right signal)
	RS	right stimulus (DS followed by unimanual stop-left signal)
Response	DR	dual response, bimanual (correct action for DS)
	NR	non-response (correct action for SS)
	LR	left response, unimanual (correct action for LS)
	RR	right response, unimanual (correct action for RS)
Measure	EMG	electromyographic activity
	RT	response time (onset of DS to button press)
	SSD	stop-signal delay (onset of DS to stop signal)
	SSRT	stop-signal RT (running time for the stop process)
Theory	ATM	Activation-Threshold Model
	SIS	Simultaneously Inhibit and Start

68 a unimanual response on selective-stop trials. The need to globally stop and then
69 subsequently restart has been used to explain why, when selective stopping is successful,
70 the unimanual response is delayed relative to the bimanual response on trials without a
71 stop signal, typically by 100-200 msec (Coxon, Stinear, & Byblow, 2007). The ATM
72 explains the common finding that unimanual EMG amplitudes are larger than bimanual

73 EMG amplitudes by the restart needing to exceed a higher activation threshold caused by
74 the global inhibition. More specifically, the ATM was developed based on variations in
75 cortico-motor excitability observed during unimanual stop trials that were taken to suggest
76 a series of three distinct processing stages, (i) a go stage: the go signal triggers preparation
77 and activation of a synchronous two-component (“bimanual”) response via neuronal
78 coupling of effector representations; (ii) a stopping stage: if the stop signal arrives before
79 EMG amplitude is sufficient to cause execution of a bimanual response, the threshold
80 activation required to do so is raised; (iii) a restart stage: a new one-component
81 (unimanual) response is then prepared and activation boosted sufficiently to overcome the
82 higher threshold and trigger a unimanual response. Simulations performed by MacDonald
83 et al. (2017) show that the delay between the onset of the second stage, which causes the
84 activation threshold to increase exponentially towards a higher level, and third stage, which
85 causes activation to increase exponentially towards an even higher level, is usually quite
86 substantial. Their Figure 5F shows the delay is at the very least 60 milliseconds (msec)
87 and usually much longer.

88 SIS instead explains selective stopping by an extension of the race-model architecture
89 applied to the standard stop-signal task, where the selective-stop signal simultaneously
90 inhibits the bimanual response and starts a new unimanual response. SIS and ATM differ
91 in three key ways, (i) rather than the second and third stages occurring in series, they
92 occur in parallel, (ii) rather than the third stage being a restart, it is constituted of an
93 entirely new selective-response process; (iii) rather than being global, the action of the
94 stopping process is specific to the bimanual runner. If the same type of inhibitory
95 mechanism is used in the standard and selective stop-signal tasks, SIS must assume its
96 stopping process will be much faster than any go process. This predicts that successful
97 stopping will typically rely on the stop runner being quick enough to overtake the bimanual
98 runner. The selective process then triggers a corresponding response some time later.
99 Unimanual responses are delayed relative to the bimanual responses simply because the

100 onset of the selective process is delayed by the SSD. This predicts that the unimanual vs.
101 manual delay is a function of the SSD, although it could be shorter than the SSD if the
102 unimanual runner is faster than the bimanual runner as indicated by EMG amplitudes.
103 However, under the unified account proposed by SIS, the go runners should rely on the
104 same neural mechanisms, and so the unimanual runner should not be much faster.
105 Similarly, if standard and selective stopping rely on the same neural mechanisms, the stop
106 runner should be much faster than either type of go runner in selective stopping.

107 Importantly the two theories make clearly contrasting predictions about the time
108 course of “partial” responses—EMG bursts insufficient to cause a response—that
109 sometimes occur in both hands on successful selective-stop trials which later have a single
110 response-generating burst in one hand. ATM predicts a gap between partial responses and
111 the unimanual response due to the need to restart. A partial response occurs when EMG
112 activity increases as activation approaches but does not reach the response threshold before
113 the stopping process elevates the threshold, causing EMG activity to decline before it is
114 sufficient to trigger a response. There is then necessarily a delay before the restart process
115 can boost activation sufficiently to cross the new higher threshold. SIS, in contrast, predicts
116 that partial bursts can occur any time up to just before the unimanual response depending
117 on the margin between the finishing times of inhibitory, bimanual, and unimanual runners.
118 That is, if the stop runner arrives before a sufficient amplitude is generated to trigger a
119 bimanual response and causes EMG in both hands to start to decrease it is still possible
120 that a fast unimanual runner might arrive very soon after, causing EMG to increase in the
121 corresponding hand while it continues to decrease in the other hand.

122 If running times are as variable in selective stopping as they are known to be in the
123 standard paradigm (Matzke et al., 2013), such “blending” of partial and
124 response-generating bursts should be sufficiently common to be detectable. To enhance
125 measurement of partial bursts and our ability to detect any gap we used both stiff and
126 conventional compliant response buttons in our experiment. To foreshadow our results, for

127 both button types, our EMG analysis found no evidence for a gap, leading us to propose
128 the SIS model. The simple structure of SIS allowed us to implement it as a quantitative
129 cognitive model and extend the Bayesian hierarchical methods that have been successfully
130 used to estimate the distribution of SSRT in the standard paradigm (Matzke, Love, &
131 Heathcote, 2017; Matzke et al., 2013) to estimate both SSRT and unimanual runner
132 finishing time distributions in selective stopping. We simultaneously fit the SIS model to
133 response probabilities and the distributions of RTs for bimanual and unimanual responses
134 to determine whether it provides an accurate quantitative account of the data. We also
135 test the predictions that the unimanual runner is faster than the bimanual runner but the
136 stop runner is faster than both.

137 **Materials and Methods**

138 **Experimental Design**

139 **Participants.** Twenty-eight participants (ten male) aged between 19 and 40 years
140 ($M=24.1$, $SD=4.6$) undertook a single experimental session after giving informed consent;
141 the procedures had received ethical approval from the Tasmanian Human Research Ethics
142 Committee. Twenty-six participants were self-reportedly right-handed, whereas the other
143 two were left-handed. Participants were screened for neurological impairments, muscular
144 conditions that limited their ability to comfortably undertake the task, and colour
145 blindness (Ishihara, 1972).

146 **Procedure.** Participants were seated at a desk approximately 80cm away from a
147 computer monitor with forearms pronated and resting comfortably on the desk. Each index
148 finger rested on a button, with the buttons positioned approximately shoulder width apart.
149 Following initial on-screen instructions (together with verbal explanations to provide any
150 clarification), participants were required to respond to visual stimuli created in PsychoPy
151 (Peirce, 2009) presented on a black background by pressing the buttons. They completed
152 1260 trials (60 practice trials and 1200 experimental trials) in a single experimental session

153 in the laboratory, which lasted no more than two hours. Breaks were administered between
 154 each 120-trial block to prevent fatigue, with a longer break after 630 trials, if desired.

155 We manipulated the force required to register a response to the visual stimuli by
 156 using two sets of response buttons - either stiff or compliant, which respectively required
 157 7.4 or 1.0 Newton of force to generate a response. The buttons were swapped half way
 158 during the experiment (the order of button use was counterbalanced across participants),
 159 but the procedure with each button type was otherwise identical.

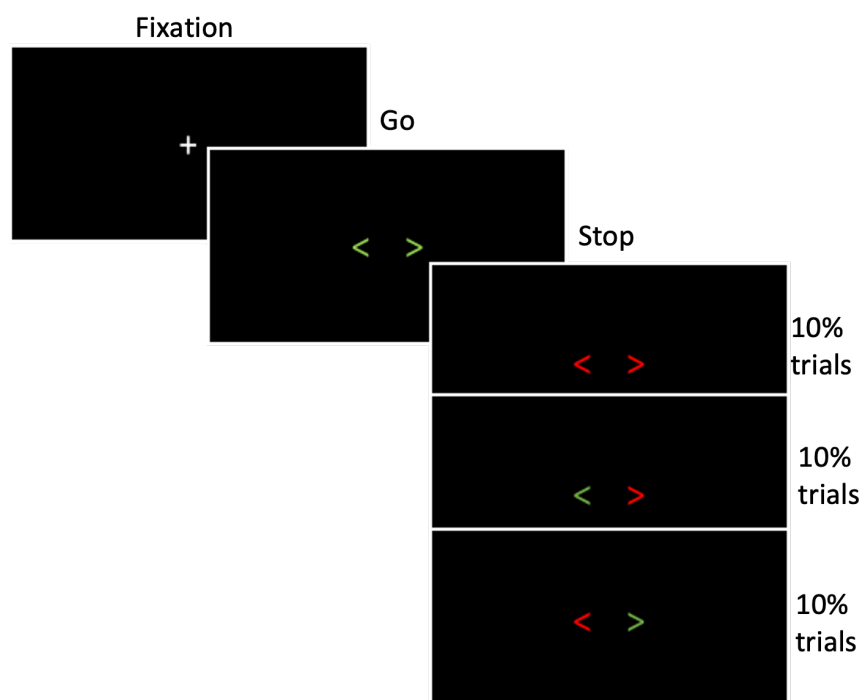


Figure 2. The presentation of the stop-signal task visual stimuli in the current study. A centrally located fixation cross was presented for between 500-700 msec. At the offset of the fixation cross, the go stimulus would then appear for 500 msec. On 30% of trials, the imperative go signal changed to the stop signal at SSD msec after presentation of the go stimulus. The 30% of stop trials were comprised of 10% of each stop type (bimanual stop, left stop, right stop).

160 On each trial, a fixation cross was presented for 500-700 msec (uniformly distributed)

161 in the centre of the screen at the start of each trial; the jittering of presentation period was
162 designed to prevent temporal prediction of the upcoming go stimulus. Following the
163 fixation cross, two green arrows appeared (the ‘go’ stimulus), requiring fast-as-possible
164 simultaneous responses on both left and right buttons. Successful responses, defined as a
165 bimanual response occurring in a window of 150-1,500 msec after the go stimulus, were
166 followed by visual feedback of the response time for 500 msec prior to commencement of
167 the next trial. Failed responses received the feedback message ‘incorrect’, and button
168 presses after the response window received the feedback message ‘missed’. Any responses
169 faster than 150 msec were met with the feedback message ‘too fast’.

170 On 30% of trials, one or both green arrows turned red, indicating that the participant
171 must try to cancel the response on the same side as the red arrow. Thus, some stop trials
172 required both left and right responses to be cancelled (both arrows turn red: ‘bimanual
173 stop’), whereas others required only one response to be cancelled while the other response
174 continued (either the left or the right arrow turns red: left or right stop – ‘selective stops’).
175 Each of the three stop types was equally likely (10% of all trials) and presented in a
176 pseudo-randomized order. The delay between the onset of the ‘go’ and ‘stop’ stimuli
177 (stop-signal delay, SSD), was staircased in 50 msec increments based on whether or not
178 participants successfully cancelled their response on the previous stop trial: Successful
179 inhibition resulted in longer SSD on the subsequent stop trial, whereas failed inhibition
180 resulted in shorter SSD on the subsequent trial. SSD was incremented independently for
181 each stop type, and re-set to 150 msec at the start of each 120-trial block. Successfully
182 inhibited trials were followed by the message ‘good’ presented on the screen, whereas failed
183 inhibitions were provided with the feedback message ‘incorrect’.

184 Each participant undertook a total of 630 trials with each button type: 30 practice
185 trials with three stop trials of each variant, followed by 5 blocks of 120 trials, each
186 constituted of 90 go trials, 10 bimanual stop, 10 left stop and 10 right stop trials. Practice
187 trials were not used in the analyses.

188 **Electromyographic (EMG) recordings.** EMG signals were recorded using
189 adhesive electrodes (Ag/AgCl) positioned in a belly-tendon montage on the first dorsal
190 interosseous (FDI) muscle of each hand, with a ground electrode positioned on the ulnar
191 bone on each wrist. The analogue signals were band-pass filtered at 20–1,000 Hz, amplified
192 1,000 times, sampled at 2,000 Hz (CED Power 1401 and CED 1902, Cambridge, UK) and
193 saved into a PC for offline analysis. Prior to commencing the task, participants were
194 provided with initial visual feedback of the EMG signal (biofeedback) to ensure they
195 completely relaxed their muscles. If signals became noisy during the experiment (i.e.,
196 unintended activation of the muscles, not related prior to the presentation of stimuli), the
197 experimenter instructed the participant to relax their hands.

198 **Statistical Analysis**

199 **Behavioral Data.** Raw behavioral data, and a script in the R language that
200 prepares it for further analysis (prepareData.R) are provided in supplementary materials at
201 <https://osf.io/5z9vk/>. Consistent with the standard assumption that neuronal coupling
202 of effector representation typically produces bimanual responses, RTs for left and right
203 button presses were typically very close to synchronous. Coupling was reflected in the
204 standard deviation of right - left RT (38ms) being much less than predicted assuming
205 independence (median 180ms, bootstrap 95% confidence interval 179-182 msec). However,
206 occasionally, bimanual responses were asynchronous with difference intervals ranging up to
207 1,000 msec. Based on inspection of the histogram of differences (see prepareData.R at
208 <https://osf.io/5z9vk/>) we removed all bimanual responses with asynchrony greater
209 than 60 msec (1.9% of trials overall, 0.1% to 5.8% on an individual basis) from further
210 analysis. We treated the remaining differences due to motor noise by averaging the left and
211 right button press times to produce a single RT measure for bimanual response trials. We
212 also removed trials with RTs less than 200 msec (0.13%), as they are very likely to be
213 anticipatory responses which are too fast to have been triggered by the go stimulus.

214 For all trial types, participants occasionally made unusual errors. On dual-stimulus
215 (DS) trials (i.e., trials without a stop signal), they constituted either no response or a
216 unimanual left or right response (0.7%, 0.5% or 0.4% of this trial type). On dual stop (SS)
217 trials (i.e., trials with two red arrows), they are unimanual left or right responses (2% each).
218 On unimanual left-stimulus (LS) trials (i.e., red arrow on the right), they are unimanual
219 right responses or no response (1.2% and 0.3%) and on unimanual right-stimulus (RS)
220 trials, they are unimanual left responses or no response (0.9% and 0.5%).

221 Here we report results for the basic SIS model that does not account for these
222 unusual responses, and so they were removed from the modelling analyses (1.4% of trials
223 overall, 0.2% to 5.1% on an individual basis). We also developed an extended model that
224 does account for these rare unusual responses in a descriptive manner on the assumption
225 that they are produced by motor errors. We do not make any strong claims about the
226 motor-error account given the rarity of the associated responses makes inference about
227 them very uncertain. However, in supplementary materials we provide detailed results for
228 the extended model to demonstrate they are consistent with the results for the basic model
229 reported here, showing that omitting the unusual responses has no material impact on
230 substantive conclusions in this case. On the OSF website, we provide R code to fit both
231 basic and extended models using hierarchical Bayesian methods implemented through the
232 Dynamic Models of Choice software (DMC; Heathcote et al., 2019). Supplementary
233 materials also provide a formal specification of the basic and extended models.

234 We fit the models in a Bayesian hierarchical manner (Matzke, Dolan, Batchelder, &
235 Wagenmakers, 2015; Shiffrin, Lee, Kim, & Wagenmakers, 2008) using the default settings
236 in the DMC software, which implements differential evolution Markov chain Monte Carlo
237 sampling (Turner, Sederberg, Brown, & Steyvers, 2013) to obtain samples from the
238 posterior distribution. Specifically, we started by fitting each participant's data separately.
239 These individual estimates were used as the start points for the hierarchical fitting. Then
240 we ran the hierarchical fitting in an automatic manner until the chains had converged to

241 the posterior using the DMC function `h.run.converge.dmc`. Finally, we ran the chains for
242 250 more iterations using the DMC function `h.run.dmc`. These final iterations were used
243 for all analyses. Convergence of the MCMC chains was assessed by visual inspection and
244 the \hat{R} statistic (Brooks & Gelman, 1998) which was below 1.1 for all parameters.

245 The prior distributions that we used for the group-level parameters are displayed in
246 Table 2 along with their definitions. The times for bimanual and unimanual runners to
247 trigger a response, and for the stop runner to inhibit the go runner, are described by
248 separate ex-Gaussian distributions, which are the convolution of a normal distribution
249 (with mean μ and standard deviation σ) and an exponential distribution (with mean τ).
250 The ex-Gaussian distribution, is positively skewed, with mean $\mu + \tau$, variance $\sigma^2 + \tau^2$, and
251 third central moment given by $2 \times \tau^3$ relating to the skewness of the distribution.
252 Differences between responses made with stiff and compliant buttons were accounted for by
253 allowing different normal means for both bimanual and unimanual runners. With
254 probability p_{TF} the model also allowed for the possibility that the stop signal may fail to
255 trigger the stop runner (Matzke, Love, & Heathcote, 2017), indicating a lapse of attention
256 to task goals.

257 **EMG Analysis.** The EMG signals were digitally filtered using a fourth-order
258 band-pass Butterworth filter at 20–500 Hz. EMG envelopes were obtained by full-wave
259 rectification and low-pass filtering at 10 Hz, and used to extract all EMG parameters,
260 except for onset and offset times.

261 We used a single-threshold algorithm (Hodges & Bui, 1996) to detect the precise
262 times of onset and offset of EMG bursts. Signals were rectified and smoothed by low-pass
263 filtering at 50 Hz. A moving average with a window of 500 msec was used to find the
264 segment with the lowest RMS amplitude (baseline), and EMG bursts were identified when
265 the amplitude was above 3 SD from baseline. For robustness, EMG bursts separated by
266 less than 20 msec were merged together.

267 From the EMG onsets and offsets detected, we set time constraints to identify up to

Table 2

The prior distributions for the group-level mean parameters were all truncated normal distributions with the below specified location, scale, lower bound, and upper bound. The priors on the group-level standard deviations were exponential distributions with the rate parameter set to 1. Note that the prior for the trigger failure parameter P_{TF} was specified on the probit scale (Φ^{-1} denotes the probit transformation).

Type	Parameter	Location	Scale	Lower Bound	Upper Bound
Bimanual normal mean	$\mu^{\text{compliant}}$	0.4	1	0	2
Bimanual normal mean	μ^{stiff}	0.4	1	0	2
Bimanual normal SD	σ	0.05	1	0	0.5
Bimanual exponential mean	τ	0.15	1	0	0.5
Stop normal mean	$\mu_{\text{stop}}^{\text{compliant}}$	0.2	1	0	2
Stop normal mean	$\mu_{\text{stop}}^{\text{stiff}}$	0.2	1	0	2
Stop normal SD	σ_{stop}	0.025	1	0	0.5
Stop exponential mean	τ_{stop}	0.075	1	0	0.5
Unimanual normal mean	$\mu_{\text{U}}^{\text{compliant}}$	0.4	1	0	2
Unimanual normal mean	$\mu_{\text{U}}^{\text{stiff}}$	0.4	1	0	2
Unimanual normal SD	σ_{U}	0.05	1	0	0.5
Unimanual exponential mean	τ_{U}	0.15	1	0	0.5
Probability of trigger failure	P_{TF}	$\Phi^{-1}(0.1)$	1	-6	6

268 two bursts of interest: First, the RT-generating burst was identified as the last burst where
 269 GO-signal < onset < [RT - 100 msec]. In addition, some trials exhibited partial bursts,
 270 i.e., EMG bursts that were not strong enough to generate a button press. In successful stop

271 trials, partial bursts represent motor commands that, although initiated, were cancelled in
272 response to the stop signal. Based on theoretical considerations that match our model
273 assumptions, partial bursts were identified in each hand as the earliest burst where (i)
274 EMG offset $>$ SSD (i.e., the initial bimanual response is cancelled after presentation of the
275 stop signal); (ii) time of peak EMG $<$ onset of RT-generating burst from the responding
276 hand (i.e., the EMG associated with the new unimanual response must commence [i.e., an
277 onset is detected] after the EMG associated with the initial bimanual / partial response
278 begins to decrease [i.e., after its peak is detected]); and (iii) peak EMG amplitude $>$ 20%
279 of the average peak from successful bimanual go trials (avoid inclusion of spurious muscle
280 activity unrelated to the task). In bimanual stop trials, in the absence of an RT-generating
281 burst, we estimated an upper time constraint for the time of peak partial burst, i.e.,
282 condition (ii), that would be comparable to the one used in selective-stop trials: The 90th
283 percentile from the distribution of EMG onsets of the RT-generating burst from successful
284 selective-stop trials. These time and amplitude constraints were critical to avoid inclusion
285 of spurious bursts, in particular those initiated together with or after the RT-generating
286 burst, which are likely related to mirror activity or other spurious muscle activity unrelated
287 to the stop-signal task.

288 From each burst detected (RT-generating and partial), we extracted the times of
289 onset, peak and offset, as well as the peak amplitude and peak slope (also called rate of
290 EMG onset) from the EMG envelopes. The amplitude of EMG envelopes from each hand
291 was normalised by the average peak EMG from successful bimanual go trials,
292 independently for stiff and compliant buttons. We used generalised linear mixed models
293 (GLMMs) to compare the parameters extracted across trial types.

294

Results

295 We denote the four trial types occurring in the experiment in terms of the stimulus
296 that defines the behaviour desired of the participant: 1) dual stimulus (DS, two green

297 arrows), requiring a bimanual go response; 2) stop stimulus (SS, two red arrows), requiring
298 both left and right responses be withheld, i.e., bimanual stop; 3) left stimulus (LS, green
299 left arrow and red right arrow), requiring a unimanual left response; and 4) right stimulus
300 (RS, red left arrow and green right arrow), requiring a unimanual right response. The four
301 corresponding trial outcomes are: 1) a dual response (DR, i.e., bimanual button press); 2)
302 a non-response (NR, i.e., no button press); 3) a left response (LR, i.e., unimanual left
303 button press); and 4) a right response (RR, i.e., unimanual right button press).

304 The results reported here focus on the seven most common stimulus-response
305 combinations, which are predicted by both theories that we test: SS-NR, SS-DR, DS-DR,
306 LS-LR, LS-DR, RS-RR and RS-DR (98.5% of the data). In supplementary materials
307 (<https://osf.io/5z9vk/>), we show that an extension of SIS is able to accurately account
308 for all stimulus-response combinations by allowing for motor errors (i.e., slips of the finger
309 causing the wrong button to be pressed or responses too weak to cause a button press to
310 be recorded).

311 Behavioural and EMG Results

312 Figure 3 shows the behavioural and EMG profiles obtained using stiff buttons; similar
313 results for compliant buttons can be seen in the supplementary material. The left panel on
314 the top row of Figure 3 shows the fundamental signature of the standard race model: RT
315 on failed bimanual stop trials (i.e., SS-DR) is faster than on bimanual go trials (i.e.,
316 DS-DR), because slow dual-response runners tend to loose to inhibitory runners more often
317 than fast dual-response runners (GLMM $p < 0.001$, all post hoc $p < 0.001$). This is also
318 true for failed trials requiring selective stopping (i.e., L/RS-DR). In contrast, a substantial
319 stopping delay relative to trials without a stop signal is evident for successful unimanual
320 responses (i.e., L/RS-L/RR), with the delay being larger when there is a partial response.

321 The second panel on the top row of Figure 3 shows that, as expected, trials on which
322 stopping failed (either bimanual or unimanual) have longer SSDs (which was set by a

323 staircase algorithm, see Materials and Methods) than trials where stopping succeeded
324 (GLMM $p < 0.001$, post hoc $p < 0.001$). On successful bimanual stop trials, there is little
325 difference in average SSD between trials with and without partial responses. However,
326 unimanual stop trials with partial responses have longer SSDs (post hoc $p = 0.01$),
327 consistent with there being more time for the initiation of a (partial) dual response to
328 begin before it is terminated by inhibition. The third panel on the top row of Figure 3
329 plots RT with SSD subtracted (i.e., “relative” RT). Relative RT is very quick on failed stop
330 trials, consistent with dual responses being triggered by the go stimulus (GLMM $p <$
331 0.001). Consistent with the unimanual runner being triggered by the selective stop signal,
332 and being faster than the bimanual runner, relative RT from unimanual responses is
333 slightly faster than RT from bimanual trials with no stop signal (post hoc $p < 0.001$). The
334 difference between unimanual trials with and without a partial response is also attenuated
335 by removing the systematic difference between them in SSD (post hoc $p < 0.001$).

336 The bottom row of Figure 3 compares the peak EMG amplitude, the relative onset of
337 RT-generating burst (relative to SSD), and its length. There is no evidence of a difference
338 among these statistics between successful bimanual go trials or failed (bimanual or
339 unimanual) stop trials (GLMM $p < 0.001$, post hoc both $p > 0.6$). In contrast, EMG
340 amplitude is elevated on successful selective-stop trials (GLMM $p < 0.001$, post hoc both p
341 < 0.001), consistent with relative RT being faster for these trials than for trials with no
342 stop signal. Moreover, unimanual trials with partial bursts show later relative onsets of
343 EMG than trials without partial bursts (post hoc $p < 0.001$).

344 Figure 4 shows, for each trial type, the average EMG profiles obtained using the stiff
345 buttons collapsed over left and right hands (analogous results for compliant buttons are
346 given in supplementary materials). The top row shows responses to bimanual go and stop
347 trials and the second row shows responses to unimanual stop trials, where the responding
348 and stopping hands are represented by solid and dashed lines, respectively. In each column,
349 the profiles were referenced to a different time event in order to highlight distinct aspects of

350 the EMG responses. Note that, because EMG profiles were normalised to the average peak
351 of the RT-generating burst, the amplitude of successful bimanual go trials is 1 when all
352 peaks are aligned (i.e., “Ref: peak EMG”, right-most column). As the reference is moved
353 away from the peak EMG, the shape and timing of the average EMG profiles blur as a
354 result of time-averaging individual profiles whose peaks are not perfectly aligned.

355 When the EMG profiles are referenced to the go signal (“Ref: GO”), it is clear that
356 responses on failed stop trials (both SS-DR and L/RS-DR) happened earlier than on
357 successful bimanual go trials, i.e., they had an earlier EMG onset and peak latency. Also,
358 note the similarity of responses between bimanual and unimanual failed stop trials, as both
359 correspond to imperative bimanual responses that were not successfully cancelled.

360 Profiles referenced to the stop signal (“Ref: STOP”) highlight the strong dependence
361 between SSD and responses during selective-stop trials. Consistent with Jana, Hannah,
362 Muralidharan, and Aron (2020), failed stop trials show the largest SSDs, followed by
363 successful trials with partial responses then trials without partial responses (see Figure 3).
364 This reflects that, on failed stop trials, the stop signal was presented too late for the
365 already large EMG response to be cancelled. On successful stop trials with partial bursts,
366 although the bimanual response had already been initiated when the stop signal was
367 presented, it was still small enough to allow for cancellation. Finally, on successful stop
368 trials with no partial bursts, the stop signal was presented early enough so no significant
369 bimanual EMG activity had been initiated. Furthermore, note that, during successful
370 unimanual stop trials, the EMG profiles of the responding and stopping hands (solid and
371 dashed lines) are nearly identical before the onset of the RT-generation burst. We applied
372 statistical parametric mapping to compare the EMG profiles between the responding and
373 stopping hands, which confirmed that they differ significantly only 180 msec after the stop
374 signal, during initiation of the unimanual response.

375 Profiles referenced to EMG onset show (i) strong similarity between responses to
376 successful bimanual and failed stop trials (top row), in addition to (ii) a clear separation

377 between partial and RT-generating bursts during successful selective-stop trials (second
378 row). Note that the algorithm used to detect EMG bursts requires that the EMG
379 amplitude returns to baseline levels for at least 20 msec between the partial and main
380 responses, otherwise they are identified as a single burst.

381 In profiles referenced to peak EMG, the dotted horizontal line marks the average
382 (normalised) amplitude of the RT-generating burst during successful bimanual go trials.
383 These plots indicate that the amplitude of the EMG response is similar during successful
384 and failed bimanual trials, whereas successful unimanual responses show higher peak EMG
385 amplitude, as highlighted on the small inlet plot.

386 As expected, partial bursts were smaller than RT-generating bursts: Considering
387 successful unimanual trials, the partial bursts have lower normalised amplitude (average
388 partial vs. RT-generating: 0.51 vs. 1.12), slower rate of onset (8.8 vs. 19.5), and shorter
389 duration (91 vs. 192 msec) than RT-generating bursts of the same (i.e., responding) hand.

390 **Merging of partial and RT-generating bursts**

391 We developed a robust algorithm to detect partial EMG bursts independently in the
392 responding and stopping hands. The algorithm avoids detecting partial bursts that
393 previous analyses have reported as occurring together with, or after, the RT-generating
394 burst (Raud et al., 2020) – which likely correspond to mirror activity or other spurious
395 muscle activation not related to the stop-signal task. Briefly (see Materials and Methods
396 for full details), for each trial we find all EMG bursts using a single-threshold EMG onset
397 detection algorithm (Hodges & Bui, 1996), and a partial burst is identified when (i) the
398 offset happens after the stop signal; (ii) the peak latency happens before the onset of the
399 RT-generating burst; and (iii) the normalised peak amplitude is at least 0.2. These
400 conditions were necessary to ensure we select only bursts corresponding to activity that
401 was cancelled in response to the stop signal.

402 In Figure 5-A, we present the entire distribution of successful single-trial EMG

403 responses to unimanual trials by pooling together data from all subjects, separated by stop
404 and responding hands. The EMG profile from each trial is represented by a horizontal line,
405 colour-coded by normalised amplitude, and referenced to the time of the peak
406 RT-generating burst of the responding hand. To represent variations in the timing of
407 partial bursts, successful trials with partial bursts are displayed at the bottom, sorted by
408 the delay between the peaks of partial and RT-generating bursts, and thus illustrate the
409 complete distribution of timing between the two bursts across our entire data set. The
410 partial bursts, when present, correspond to cancelled bimanual responses, and usually (65%
411 of the times for stiff buttons) happen on both hands simultaneously, with an average
412 difference in the onset of partial bursts between hands of only 14 msec.

413 However, there were other trials where the EMG amplitude did not return to baseline
414 after an initial response, but rather the partial burst merges with the RT-generating burst,
415 resulting in a single burst with a long tail (i.e. skewed) to the left, prior to peak EMG. To
416 represent the temporal relationship between partial and RT-generating bursts, we sorted
417 the remaining trials (successful stop trials with no partial response) based on the average
418 amplitude in the period between -160 and -80 msec from the peak EMG of the responding
419 hand. The results provide evidence that, rather than a clear delay to the main response,
420 the stopping delay manifests as a continuous distribution of timing between the partial and
421 the RT-generating bursts. On some trials, the delay is large enough to allow clear
422 separation between bursts; on other trials, the delay is shorter until it becomes less than
423 the precision of our EMG detection algorithm, and hence it becomes impossible to
424 distinguish the two bursts, as they merge into a single burst.

425 Figure 5-C shows the distribution of the delays between the partial and RT-generating
426 bursts, both between the burst peaks, and the length of the silent period between bursts,
427 i.e., the time between the offset of the partial and the onset of the RT-generating
428 responses. The delay between peaks has a uni-modal distribution and is comprised only of
429 positive values. Consistent with the merging between bursts evident qualitatively in Figure

430 5-A, the silent period shows a distribution skewed towards small values, bordering on the
431 20 msec limit of our EMG onset detection algorithm for a large number of trials.

432 Figures 5-B and 5-D show analogous results for compliant buttons. Compared with
433 the stiff button, responses using the compliant button had much smaller percentage of
434 successful unimanual stop trials with partial bursts (14.8% vs. 51.4% of successful stop
435 trials, or 8.2% vs. 32.1% of all unimanual stop trials), in addition to a larger percentage of
436 failed stop trials (42.3% vs. 37.2%). These differences arise from the amount of force (and
437 thus length of time) it takes to generate a press with each button type: The compliant
438 button requires much less force to register a button press than the stiff button (1N vs.
439 7.4N). Hence participants have less time available to cancel the initial bimanual response
440 after they perceive the stop signal. Nevertheless, the results for the compliant buttons are
441 also consistent with a merging between partial and RT-generating bursts.

442 In summary, our results for both stiff and compliant buttons challenge the
443 global-inhibition theory, which states that cancellation of the bimanual response is followed
444 by a delay then re-initiation of a unimanual response (Coxon et al., 2007; MacDonald et
445 al., 2014, 2017). Instead, they are consistent with an independent race between a bimanual
446 runner, triggered by the go stimulus, and two runners that are triggered by the stop signal,
447 namely a stop runner that can cancel the already active bimanual go runner and a new go
448 runner that can initiate a unimanual response. If the stop runner wins, the partial response
449 is cancelled, EMG amplitude returns to baseline levels before initiation of the
450 RT-generating burst, and two distinct bursts are observed. In contrast, if the go runner
451 wins, although a temporary reduction (or distortion) in EMG amplitude may still be
452 observed prior to the peak of the RT-generating burst, the initial response is not
453 completely cancelled, and a single burst is observed. In the next section we outline the
454 details of the cognitive model we developed and fit it to our behavioural data.

455 Cognitive Modelling

456 The SIS model is based on Matzke et al.'s (2013) BEESTS model of the standard
457 stop-signal task. It is mathematically tractable, with straightforward solutions for the
458 likelihoods of all stimulus-response combinations (provided in supplementary materials)
459 enabling efficient fitting. Figure 6 graphically depicts the ways in which it accounts for the
460 seven common stimulus-response pairs occurring over the four trial types.

461 On DS trials (i.e., trials with no stop signal), the go stimulus triggers a single dual-go
462 runner that simultaneously produces the left-hand and right-hand components of a
463 bimanual response (DR) at time RT (drawn from an ex-Gaussian distribution). The unity
464 of bimanual responses is supported by the coordinated way in which they occur, with each
465 button press typically made almost simultaneously. In contrast, trial-to-trial variability in
466 RT spans a much wider time scale (e.g., $SD \approx 100$ msec), so if each button press were to
467 any appreciable degree independent, much less synchronicity would be expected (see
468 MacDonald et al., 2014, for further evidence see `prepareData.R` at
469 <https://osf.io/5z9vk/>).

470 On SS trials (i.e., trials requiring both button presses to be withheld), the stop signal
471 can trigger a stop runner, which also has an ex-Gaussian finishing time distribution.
472 However, with probability p_{TF} the stop signal may fail to trigger the stop runner (Matzke,
473 Love, & Heathcote, 2017), indicating a lapse of attention to task goals. Such “trigger
474 failures” occur at elevated levels in clinical populations, where they can explain part or
475 most of performance deficits in the standard stop-signal paradigm (Matzke, Hughes,
476 Badcock, Michie, & Heathcote, 2017; Weigard, Heathcote, Matzke, & Huang-Pollock,
477 2019). They are also found in healthy participants, usually at lower levels, but often with
478 appreciable individual differences (Matzke, Curley, Gong, & Heathcote, 2019; Matzke,
479 Love, & Heathcote, 2017), and when their effect is neglected it can lead to over-estimation
480 of SSRT (Skippen et al., 2020, 2018). Hence, we allowed for the possibility that they also
481 occurred in selective stopping. If a trigger failure occurs, processing follows the same course

482 as in a DS trial. If it does not, two outcomes are possible: the stop runner wins the race
483 and both left and right responses are withheld (i.e., a NR outcome) or the go runner wins
484 and both responses are made (i.e., a DR outcome).

485 For the remaining two trial types, LS (i.e., the go signal is followed by a stop signal
486 indicating respond left but not right) or RS (i.e., the go signal is followed by a stop signal
487 indicating respond right but not left), trigger failures may also occur with probability p_{TF} ,
488 in which case processing again follows the same course as in a DS trial. Otherwise, the stop
489 signal triggers both the stop runner and either a left runner (on LS trials), capable of
490 producing a unimanual left response, or a right runner (on RS trials), capable of producing
491 a unimanual right response. These successful unimanual responses can occur in two ways:
492 1) the stop runner wins the race, stopping the bimanual runner but not the unimanual
493 runner, which then continues, or 2) the unimanual runner beats the other two runners. If,
494 as it occurs in the standard stop-signal paradigm, a stop runner is much faster than a go
495 runner, and this extends to unimanual as well as dual-go runners, then the latter case
496 would be expected to be rare.

497 Our initial test compared versions of the model with and without trigger failures. All
498 model fitting and assessment was performed in a Bayesian manner (see Materials and
499 Methods for details), and we accompany model-based estimates with 95% credible intervals
500 to indicate uncertainty (Morey, Hoekstra, Rouder, Lee, & Wagenmakers, 2016).¹ We
501 selected between models using Ando's (2010) BPIC criterion, which balances the extra
502 model flexibility, and hence better fit to the present data, afforded by adding trigger failures
503 against the potential for over-fitting, and hence poorer prediction of new data. BPIC
504 favored trigger failures by a margin of 115, providing very strong evidence that they should
505 be included in the model. Although on average the percentage of trigger failures was small
506 (0.8%, with 95% credible interval [0.4% - 1.5%]), there was substantial individual variation,

¹ A 95% credible interval ranging from x to y contains 95% of the posterior mass and thus indicates that one can be 95% confident that the true value lies between x and y .

507 with trigger failures occurring on 10.1% [3.7% - 14.5%] of trials for one participant. In light
508 of these results, we selected the model with trigger failures for further analysis.

509 Figure 7 shows model fit, with a similar pattern of performance, but slightly faster
510 responding, for compliant relative to stiff buttons. Failures of stopping (i.e., dual
511 responses) occurred at about the same rate in all three conditions with stop signals.
512 Substantial slowing of unimanual responses relative to dual responses is evident. The figure
513 also shows that the race model's signature prediction, faster responding with than without
514 a stop signal, occurs to the same extent for selective and non-selective stopping, and
515 increases as responses slow, so that it is quite substantial for the 90th percentile. The
516 model captures all of these effects, including the fine-grained effects on RT distributions.

517 Estimates of the model's parameters are provided in Table 3. Figure 8 combines
518 parameters to show the model's estimates of the average speed of the runners. The time for
519 the dual-stop runner, which corresponds to SSRT, is much faster than the times for the go
520 runners, just as is the case in the standard stop-signal paradigm. However, it is also slower
521 in an absolute sense than the SSRT from the standard paradigm for comparable
522 populations performing the same type of easy choice task, which is typically considerably
523 less than 200 msec when trigger failures are taken into account (Skippen et al., 2020).
524 Table 3 also shows that slowing due to stiff buttons (accounted for in the μ parameter) was
525 slightly larger for bimanual than unimanual responses, and that trigger failures were rare,
526 suggesting that participants were highly engaged with the task.

527 Figure 8 also shows that the unimanual runner is slower than the stop runner. As a
528 result, it rarely beats the stop runner, and so most unimanual responses occur after the
529 stop runner first beats the bimanual runner. The unimanual runner is, however, faster than
530 the bimanual runner, consistent with our behavioural findings, and that of others
531 (MacDonald et al., 2014, 2017).

Table 3

Parameter estimates for the basic SIS model. Displayed are the posterior medians (i.e., 50%) for the group-level means, accompanied by 95% credible intervals (i.e., 2.5% and 97.5%). Estimates for P_{TF} have been converted from the probit to the probability scale for easier interpretation.

Parameter	2.5%	50%	97.5%
$\mu^{\text{compliant}}$	0.37	0.40	0.43
μ^{stiff}	0.42	0.46	0.49
σ	0.05	0.06	0.06
τ	0.05	0.06	0.07
$\mu_{\text{stop}}^{\text{compliant}}$	0.20	0.21	0.22
$\mu_{\text{stop}}^{\text{stiff}}$	0.21	0.22	0.23
σ_{stop}	0.00	0.01	0.03
τ_{stop}	0.00	0.01	0.02
$\mu_{\text{U}}^{\text{compliant}}$	0.36	0.38	0.39
$\mu_{\text{U}}^{\text{stiff}}$	0.41	0.42	0.43
σ_{U}	0.05	0.06	0.07
τ_{U}	0.01	0.03	0.04
P_{TF}	0.00	0.01	0.02

Discussion

532

533 Previous investigations of selective stopping suggested that a global stop mechanism,
 534 which quickly cancels both components of an initial multicomponent action, is followed by
 535 a subsequent restart of the component of the initial action that was not required to stop

536 (MacDonald et al., 2014, 2017). Here, we present novel and converging lines of evidence
537 that support a reconceptualization of the mechanisms underlying selective stopping.

538 We utilized a bimanual response task requiring simultaneous button presses with left
539 and right index fingers (a bimanual go response), with the subsequent stop signal
540 necessitating cancellation of either one or both button presses. Our cognitive model, which
541 provided a highly accurate account of the behavioral data, suggests that selective stopping
542 is accomplished by the same type of independent race architecture that accurately
543 characterizes non-selective stopping (i.e., as assessed using a standard stop-signal task),
544 but with the addition that a selective-stop signal simultaneously triggers not only a stop
545 runner but also a new unimanual go runner. Specifically, the bimanual go runner
546 commences upon presentation of the go stimulus, and races against the stop runner that
547 commences upon presentation of the stop stimulus, irrespective of whether that stimulus
548 requires both, or only one, component of the original action to be cancelled. If successful,
549 the stop runner cancels the initial bimanual response. If the stop signal also indicates that
550 selective stopping is required, a unimanual go runner that can trigger the non-stopping
551 hand also joins the race at the time of stop-signal presentation.

552 There are potential performance advantages to this parallel processing architecture
553 compared to a serial architecture where a unimanual response component is re-initiated
554 after successful stopping has occurred (MacDonald et al., 2017). Typically, in our model
555 fits for selective-stop trials, the fast stop process causes the initial bimanual action to be
556 withheld only shortly before the slower unimanual runner produces the required (left or
557 right) response. The stopping delay, characteristic of selective-stopping tasks and
558 replicated in our data (~ 100 msec), is thus a consequence of a new unimanual go response
559 being triggered by the stop signal, which is delayed relative to the go signal. Interestingly,
560 however, typical SSDs are a little longer than this stopping delay. This is consistent with
561 the model fits that indicate unimanual go runners are slightly faster than the dual go
562 runners for both the stiff and compliant buttons (Figure 5), which partially mitigates the

563 stopping delay despite the substantially later start time. Our behavioural data indicate
564 that RTs on successful selective-stop trials, calculated relative to the stop signal, are faster
565 than the standard bimanual response times (Fig 2A – Relative RT panel), corroborating
566 the conclusions drawn from model fits. Moreover, our EMG measures also suggest that
567 unimanual responses during successful selective-stop trials are faster (earlier EMG onset)
568 and stronger (higher peak EMG amplitude) than the initial bimanual responses. Finally,
569 despite the model allowing flexibility for the stop process to vary between stiff and
570 compliant buttons, the fits suggest that this stopping process was invariant over button
571 types. Accordingly, the cancellation process was unaffected by both the nature of the stop
572 (selective or bimanual) or the mechanics of the cancelled response (stiff or compliant
573 buttons), reflecting its fast and relatively automatic nature.

574 Overall, and in contrast to the standard independent race model, our new model
575 provides a way of estimating SSRT in selective-stopping paradigms that has a clear
576 justification in terms of a plausible cognitive and neural process, and thus we recommend
577 its use. To this end, we make the methods used to fit the SIS model openly available
578 (<https://osf.io/5z9vk/>). We also note that SIS may be applicable to other types of
579 complex stopping, such as stop-change paradigms where the stop signal indicates that an
580 ongoing choice response must be changed to the alternative choice response (see Camalier
581 et al., 2007, for a similar proposal).

582 Single trial analysis of overt and covert EMG (i.e., muscle activation above and below
583 the threshold for generating a button press: ‘RT-generating’ and ‘partial’ bursts,
584 respectively) fully support the conclusions drawn from the cognitive modelling. We
585 imposed tight temporal constraints on when the overt and (preceding) partial responses
586 could be detected, based upon expected response times and the model framework. This
587 enabled us to make significant advances to recent work in this field (e.g. Raud et al., 2020;
588 Raud, Thunberg, & Huster, 2022) and ensured that all partial bursts detected were related
589 to cancellation of initiated (bimanual) actions. On selective-stop trials, we were able to

590 reliably capture both partial and RT-generating bursts in the same hand (the non-stopping
591 effector). These partial bursts were observed when responding with the stiff buttons on
592 approximately half of successfully inhibited trials, irrespective of whether the required
593 stopping was bimanual or selective, validating the model-based conclusion that the
594 stopping mechanism was invariant across stop types. The partial burst, when observed,
595 was commonly ($\sim 65\%$ of such trials) detected simultaneously in the stopping as well as
596 the responding hand, indicative of cancellation of the initial bimanual response.

597 Critically, in successful selective-stop trials with partial bursts, the temporal
598 separation between the partial and subsequent RT-generating bursts followed a continuous
599 distribution, with any estimated separation only constrained by the limit of our algorithm
600 to detect EMG onsets (i.e., we required a nominal 20 msec separation to characterize the
601 partial and RT bursts as being distinct). This continuum from distinct, well-defined bursts,
602 to a merging of bursts (Figure 5) is wholly consistent with the cognitive model, which
603 predicts that – based on the specific parameters of the stop and unimanual go distributions
604 – the unimanual response time approaches the time at which the bimanual response is
605 cancelled. A framework that predicts a nominal restart of one component of the initial
606 bimanual response following successful cancellation (like the ATM: MacDonald et al., 2017)
607 cannot account for this merging of the partial and subsequent RT generating bursts as a
608 non-negligible restart time is predicted.

609 Previous EMG algorithmic approaches to assess response cancellation in
610 selective-stopping tasks (for a recent review, see Raud et al., 2022) have searched for
611 partial and RT generating bursts in separate effectors (i.e., the stopping and responding
612 hands, respectively) without imposing tight temporal constraints on their identification.
613 This approach yielded an average delay between the peaks of the partial and the
614 subsequent RT burst of ~ 145 msec. However, in some cases the range of delays (“delta
615 peak” in Raud et al., 2020, Fig 3E) extends to 459 msec, with a significant proportion of
616 trials yielding negative delays up to -219 msec, where partial bursts occur after the RT

617 burst. Such instances cannot represent cancellation of the bimanual response, but rather
618 represent mirror activation during the voluntary selective response or later activity not
619 time-locked to visual responses (e.g., postural adjustments or muscle ‘twitches’). Including
620 partial EMG bursts occurring after the overt burst will result in overestimation of the key
621 measure of ‘CancelTime’, i.e. the time between presentation of the stop signal and the
622 ensuing reduction in amplitude of the muscle activity (Jana et al., 2020). We therefore
623 propose that the current measure of CancelTime derived using our EMG algorithm (~ 110
624 msec averaged across selective-stop and bimanual-stop trials) is a more accurate reflection
625 of the minimum time required to cancel initiated responses, suggesting the process is faster
626 than suggested by previous EMG measures (e.g. 148-174 msec Raud et al., 2020). The
627 short stopping latencies in our EMG data are also consistent with reports of neural braking
628 of the bimanual response 117 msec after the stop signal (MacDonald et al., 2017). Note
629 that CancelTime is necessarily a downward-biased measure of SSRT because it does not
630 take account of cases where slow stop runners lose the race. However, although SSRT is
631 conventionally thought to be greater than 200 msec (Verbruggen et al., 2019), estimates are
632 shorter when trigger failures are taken into account (e.g., 130 msec in Skippen et al., 2020).

633 A key finding is that our EMG estimates of CancelTime did not vary reliably
634 between selective-stop and bimanual-stop trials (Figure 1B, Ref: STOP; 2nd and 3rd row;
635 also Results section ‘Basic Behavioral and EMG Results’). This finding further supports
636 that the stopping mechanism does not vary between selective-stop and bimanual-stop
637 trials, and corroborates the model framework which designates a universal stop process
638 that is invariant between bimanual and selective trials. Furthermore, neither the model’s
639 SSRT estimates (Figure 5) nor the EMG estimates of CancelTime vary between stiff and
640 compliant buttons. In contrast, Raud et al. (2020) reported substantially longer
641 CancelTimes for bimanual compared to selective-stop trials, likely because of inclusion of
642 partial responses not associated with action stopping in the calculations.

643 In future work SIS could be extended, with the addition of extra assumptions, to

644 incorporate predictions about EMG in general and partial responses in particular. For
645 example, EMG could be assumed to begin to increase at some time t_{onset} before a response
646 racer finishes, and the finishing time could be mapped to a “point of no return” (t_{pnr} , likely
647 at or just after the EMG peak) after which a response cannot be inhibited. If the stop
648 runner finishes before the point of no return but after t_{onset} then a partial response results.
649 However, if the stop runner finishes at an earlier time then a “cortical stop” occurs without
650 an accompanying partial response. It is also possible that when the stop runner finishes it
651 takes some short time, $t_{inhibit}$, to start inhibiting a rising bimanual EMG burst, in which
652 case a partial response occur when it finishes between $t_{onset} - t_{inhibit}$ and $t_{pnr} - t_{inhibit}$.
653 Further, a relationship between the speed of runners and the amplitude of the EMG bursts
654 they induce would need to be specified, with our results here suggesting an inverse
655 relationship (i.e., faster runners are associated with larger magnitudes). When fitting such
656 a joint model the onset and other times might be modeled as either constants or random
657 variables, and an account would have to be taken of the resolution with which partial
658 bursts can be detected (e.g., up to 20 msec before the onset of the response generating
659 burst with our algorithm).

660 In conclusion, we present a new cognitive model that provides a parsimonious
661 explanation of the key action and inhibition processes in a response-selective inhibition
662 paradigm, which is wholly consistent with our rigorous EMG analyses. Together, the
663 model and EMG data offer additional insights into the ecologically relevant task of
664 selective stopping of planned actions, and provide robust methods to accurately measure
665 the inhibitory processes it depends on.

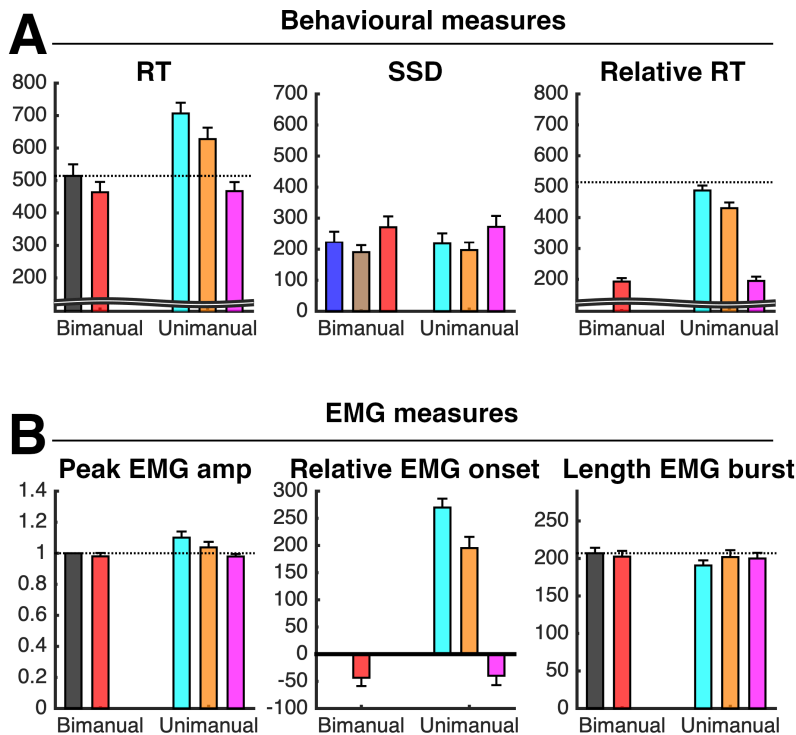


Figure legend

Trial type	Colour	Acronym	Definition	Trial description
Bimanual go / stop	■	DS-DR N: 12,084 (74.2%)	Dual stimulus – Dual response	Successful bimanual go
	■	SS-NR partial N: 396 (2.4%)	Stop stimulus – No response with partial burst	Successful bimanual stop with partial burst
	■	SS-NR no partial N: 476 (2.9%)	Stop stimulus – No response no partial burst	Successful bimanual stop no partial burst
	■	SS-DR N: 528 (3.2%)	Stop stimulus – Dual response	Failed bimanual stop
Unimanual stop	■	L/RS-L/RR partial N: 767 (4.7%)	Left/Right stimulus – Left/Right response with partial burst	Successful unimanual stop with partial burst
	■	L/RS-L/RR no partial N: 991 (6.1%)	Left/Right stimulus – Left/Right response no partial burst	Successful unimanual stop no partial burst
	■	L/RS-DR N: 1,042 (6.4%)	Left/Right stimulus – Dual response	Failed unimanual stop

Note: Rare responses were omitted, e.g., failed bimanual go trials.

Figure 3. Average results with 95% confidence intervals (CI) for responses for each trial type, using the stiff button. Successful trials were broken down by whether or not a partial response occurred, and with LS and RS results collapsed. The horizontal dotted lines represent the average for DS-DR as a reference. Compared with bimanual trials with no stop signal (DS-DR), unimanual responses showed faster relative RT and higher peak EMG amplitude, suggesting that the unimanual runner is faster and produces stronger responses than the bimanual runner. Among unimanual responses (LS-LR, RS-RR), trials with partial burst have slightly later relative EMG onset and higher EMG amplitude than those without partial bursts.

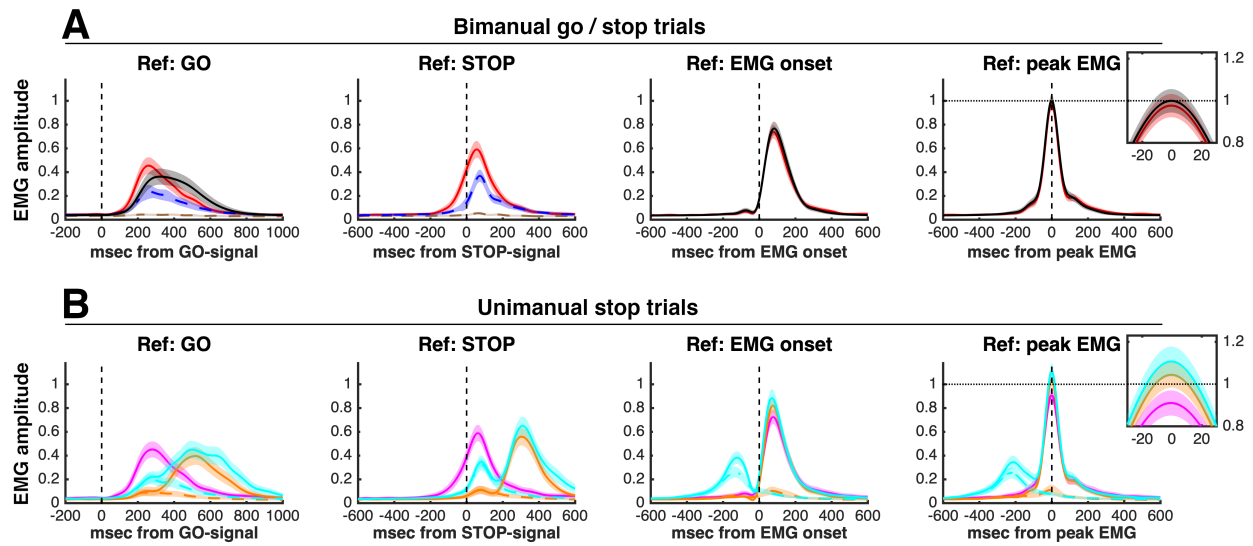


Figure 4. Average EMG profiles and 95% CI for each trial type, using the stiff buttons. Bimanual and unimanual responses are displayed in the top and bottom rows, respectively. Each column represents the same EMG profiles aligned relative to a different time reference, represented by a vertical dashed line. For selective-stopping trials, EMG profiles of responding and stopping hands are represented by solid and dashed lines, respectively.

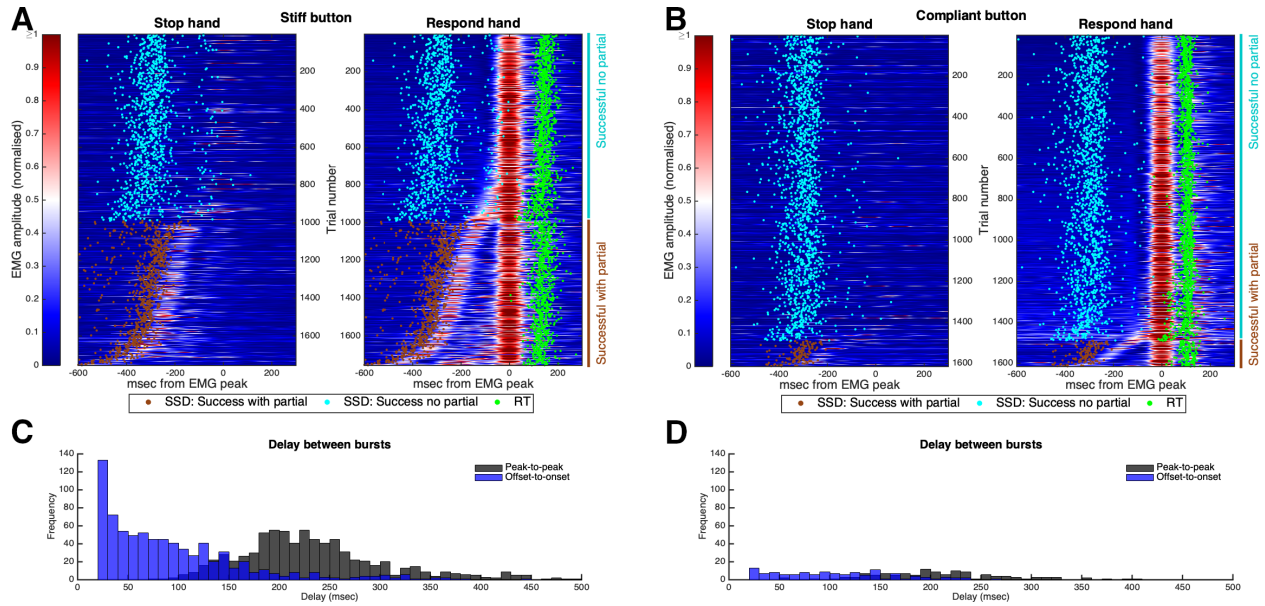


Figure 5. **A** and **B.** Single-trial EMG profiles from all subjects and trials from stiff and compliant buttons, respectively, colour-coded by normalised EMG amplitude. Signals from each trial were referenced to the peak of the RT-generating burst of the responding hand. To highlight the relative timing of partial bursts, trials with partial burst are displayed at the bottom, sorted by the distance between the partial and RT-generating bursts. Other trials were sorted by the amplitude prior to RT-generating burst. **C** and **D.** Histogram of the delay between partial and RT-generating bursts, represented as peak-to-peak or offset-to-onset times.



Figure 6. Model architecture for the four trial types: DS (go stimulus with no stop signal), SS (go stimulus followed by a signal to stop both components of the bimanual response), LS (go stimulus followed by a signal to stop the right response but continue the left response), and RS (go stimulus followed by a signal to stop the right response but continue the left response).

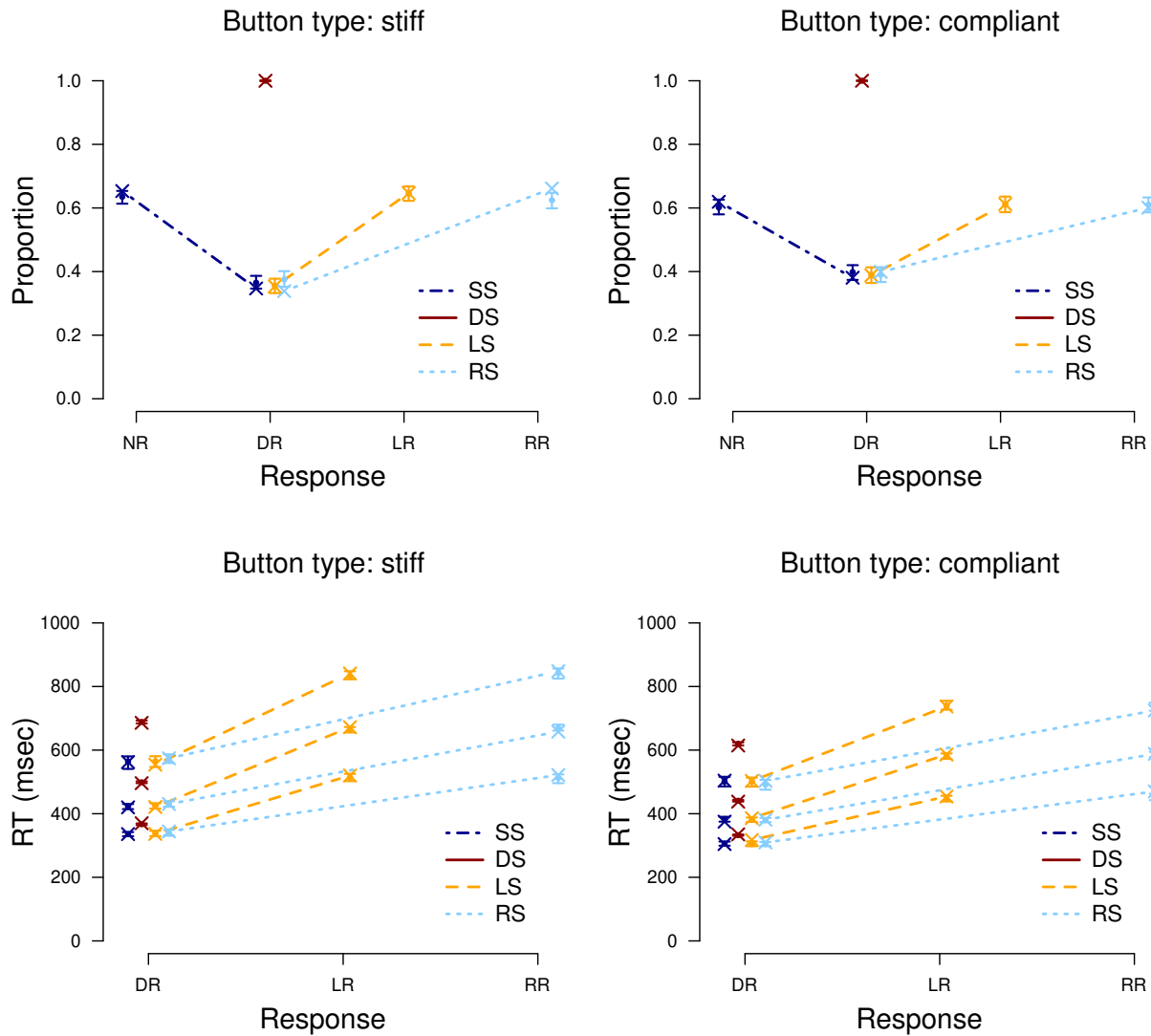


Figure 7. Fit of SIS with trigger failures. Error bars show 95% posterior predictive credible intervals generated by simulating 100 data sets based on random draws of parameter vectors from the posterior distribution. RT distributions are represented by sets of increasing points from the same condition for the 10th, 50th, and 90th percentiles. SS = dual-stop stimulus trials; DS = dual-go stimulus trials; LS = left-go stimulus trials; and RS = right-go stimulus trials. NR = no response; DR = dual (bimanual) response; LR = left unimanual response; RR = right unimanual response.

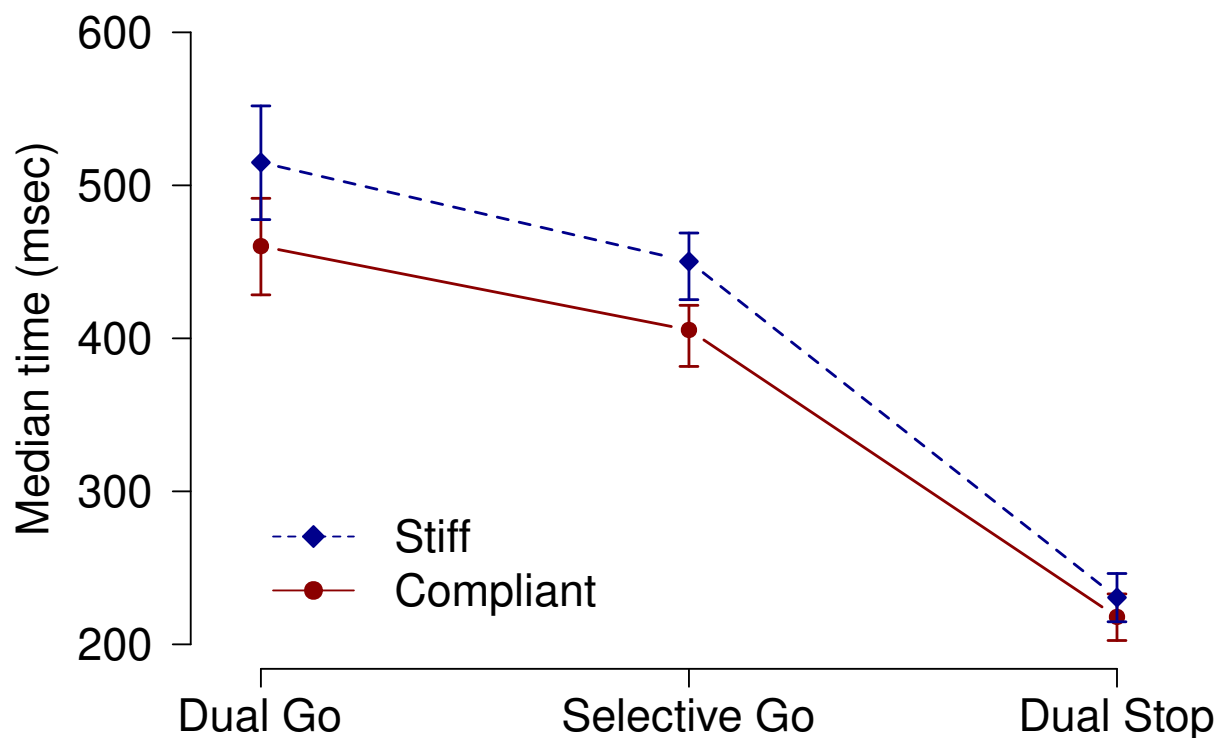


Figure 8. Average estimated running times for SIS with trigger failures in terms of the median over each participant's mean RT (i.e., $\mu + \tau$ estimates); the plot displays the posterior median estimate for this quantity accompanied by a 95% credible interval. Note that the model assumes that the left and right unimanual runners have the same speed. The individual-level estimates (not displayed) indicate that there was a meaningful difference between the running times of the dual-go and unimanual runners for both the stiff button (median difference: 60 msec, 95% credible interval: [57 msec, 64 msec]) and the compliant button (median difference: 51 msec, 95% credible interval: [47 msec, 54 msec]). However, there was no meaningful difference in running time between the stiff and the compliant dual stop runners (median difference: 13 msec, 95% credible interval: [-2 msec, 27 msec]).

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