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Stop-signal delay reflects response selection duration in stop-signal task

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Abstract
The stop-signal task (SST) is widely used for studying the speed of the latent process of response inhibition. The SST patterns are typically explained by a horse-race model (HRM) with supposed Go and Stop processes. However, HRM does not agree with the sequential-stage model of response control. As a result, the exact relationship between the response selection, the response execution stages, and the Stop process remains unclear. We propose that response selection occurs within the stop-signal delay (SSD) period, and that the competition between the Go and Stop processes occurs within the response execution period. To confirm this, we conducted two experiments. In Experiment 1, participants carried out a modified SST task with an additional stimulus category – Cued-Go. In the Cued-Go trials, cues were followed by imperative Go signals. The Cue-Go period duration was dynamically adjusted by an adaptive algorithm based on the response times reflecting the individual response selection duration. In Experiment 2, Cued-Go stimuli were followed by Stop Signals in half of the trials and response inhibition efficiency was calculated. The results of Experiment 1 indicate that SSD reflects the duration of the response selection process. The results of Experiment 2 show that this process has an independent and small effect on the effectiveness of controlled inhibition of the target response. Based on our findings, we propose a two-stage model of response inhibition in SST, with the first stage including response selection process and the second stage response inhibition following the SS presentation.

Keywords Foreperiod · Reaction time · Response inhibition · Response selection

Introduction

The *stop-signal task* (SST) is used to examine the latency of the motor inhibition process (Logan & Cowan, 1984). In a classic SST paradigm, presentation of a Go signal is followed by a Stop signal after a short delay (*stop-signal delay*, SSD), signaling that the execution of a response must be aborted. The dynamic changes of SSD in the staircase procedure depend on the success of the stopping response. After successful cancellation, the duration of the period increases, making the stopping process more difficult; after making an erroneous response, the duration of the period decreases, facilitating the stopping process. So, the relationship between the SSD duration and the response inhibition efficiency is described by the so-called "inhibition function" (Middlebrooks & Schall, 2014). The final *stop-signal response time* (SSRT) value is calculated as the difference between the *Go response time* (Go-RT) and SSD based on the assumption that the Go and stop processes are independent of each other.

The processes underlying the SST are described in the *horse-race model* (HRM; Logan & Cowan, 1984). According to the model, the presentation of Go and Stop signals triggers slower Go and faster Stop processes with stochastically independent completion times. The competition of

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these processes includes controlled and ballistic components. The Go process early in the deployment has more of the influence of the controlled component and can be cancelled successfully; in the later stages the ballistic component dominates and triggers an automatic reaction execution, which is difficult to inhibit.

According to Bissett et al. (2021), short SSDs (< 200 ms) are special because the RT increases for Error RT compared to Go-RT. Therefore, there should be a deviation from the independence between Go and Stop processes. Non-decision processes take place in the first 200 ms, so the source of this increase remains uncertain. For the longer SSD, from 200 to 500 ms, the competing go and stop processes are independent. An SSD longer than 500 ms leads to a decrease in stopping accuracy since the ballistic component of the response cannot be terminated at later implementation stages.

A closer look at the task structure suggests that the participant has to perform two tasks: (1) the choice RT (CRT) task and (2) the SST (Logan & Cowan, 1984; Logan et al., 2014; Verbruggen et al., 2019). In our opinion, the relationship between Go and Stop processes in HRM is not clear. Since the Stop process is related to the Go process, the latter must be specified in more detail. According to the *sequential stage model* (SSM; Sternberg, 2001), a motor response is a forward process that comprises independent stages of sensory analysis, response selection, and motor execution. The sensory and the motor stages carry out information processing in parallel, and therefore in serial responses their activations can overlap in time. By contrast, the response selection stage is sequential, resulting in a structural (Sigman & Dehaene, 2005; Sternberg, 2001) or strategic (Meyer & Kieras, 1997) "bottleneck" of information flow, although this sequential processing principle may be violated in boundary conditions (Zylberberg et al., 2012). The response selection processes are conceptualized in the *diffusion decision model* (DDM; Ratcliff & McKoon, 2008) as the accumulation of noisy evidence until the response threshold is reached. DDM assumes that this process is a stochastic in nature. A simpler version of DDM is a *linear ballistic accumulation* (LBA) model (Brown & Heathcote, 2008), which assumes a linear and predictable evidence accumulation process for as many accumulators as there are response options. As a result, a response whose decision process reaches the response threshold earlier will have a higher chance of being executed.

So, the HRM postulates the presence of a Go process, but it remains unclear what subcomponents the Go process comprises – response selection, response execution, or both? How do these processes relate to the time of the Stop signal presentation? What effect does the Stop process have on the Go-selection and Go-execution stages? In general, in HRM, the relationship between the stages of the Go process (selection and implementation of the response) for the CRT and the stop process for the SST remains unclear.

This issue should include a more detailed study of the processes associated with the SST structure. Although the stop process is widely investigated and conceptualized (Logan & Cowan, 1984; Verbruggen et al., 2019), SSD is used rather as a technical term in the process of calculating SSRTs than as a reflection of an underlying mental processes. Existing reports often do not provide detailed statistics as well as mean SSD values, leaving the question of the changes in different tasks and in different groups of participants unclear (Castro-Meneses & Sowman, 2018; Chao et al., 2009; van de Laar et al., 2014).

In a seminal paper (Logan & Cowan, 1984), Go process implicitly assumes stages, but explicitly Go process is calculated based on the distribution of Go-RT, that is, the final product of all stages. With the presentation of Stop Signals in some of the trials, the Stop process begins, which does not interfere with the Go process. In this case, the SSD is part of the Go process, since the subject does not know whether SS will be presented in a particular trial. If the Go process has a staging and SSRT reflects the speed of the reaction inhibition process, then SSD should reflect the complexity of response selection in the primary task. Evidence for this assumption already exists in the earliest works. For a simple reaction in the primary task, the sum of SSD and SSRT was shorter compared to the two-alternative CRT task, and subtracting SSD eliminates the difference between RT of commission errors for stop trials for the two conditions (Logan et al., 1984). Further, Logan et al. (2014) showed that an increase in the number of response options, i.e., an increase in the difficulty of response selection, in the primary task induced an increase in the duration of the SSD, but not the SSRT. In addition, the increasing complexity of sensory decision-making was found to induce an increase in SSD accompanied by unreliable changes in SSRT (Middlebrooks & Schall, 2014). However, the modality and intensity of the Stop Signal does not affect the duration of the SSD (Carrillo-de-la-Peña et al., 2019; Morein-Zamir & Kingstone, 2006). Also, children with attention deficit/hyperactivity disorder showed increased SSRT, but the SSD does not differ from typically developed children (Albajara Sáenz et al., 2020), reflecting a deficiency of voluntary control of the response, but an unaltered response selection process.

Another option to investigate the response selection process within the SST is to prepare a Go response in advance. In this case, the controlled component will reduce its influence, and the reaction with a greater presence of the ballistic component will be more difficult to cancel. Thus, a better prepared response requires a stronger inhibition process (Chikazoe et al., 2009; Ficarella & Battelli, 2019). Also, a longer prestimulus cross duration leads to a decrease in Go-RT (Wang et al., 2018) and an increase in SSRT (Li et al., 2005). The authors conclude that the ability to inhibit a motor output depends not only on the speed and the strength of the inhibitory processes but also on the status of a voluntary preparatory activation related to the Go response. In sum, the existing data suggest that the SSD in the SST structure reflects the duration of the response selection period in the primary CRT, so the competition between Go and Stop processes occurs during the response execution period.

So, we propose the following clarification of the HRM (Fig. 1). After the presentation of a Go signal and its sensory processing, a period of response selection and preparation follows, for example, pressing a right or a left key. The duration of this period is reflected in the SSD, which is dynamically adjusted to the start of the inhibition processes. At an early stage of this period (< 200 ms), the processes of inhibition and activation are inter-related (Bissett et al., 2021) and the participant can voluntarily slow down the response. Two-stage DDM modifications (Diederich & Colonius, 2021; Sun & Landy, 2016) suggest that at the first stage stochastic evidence accumulation takes place favoring one of the responses until a decision threshold is reached. As a result, the starting point may shift to initialize the subsequent motor response. This event ends the Go-selection process, which manifests itself as the mean SSD duration. Next, presentation of the Stop Signal after the sensory analysis stage initialized the response inhibition process, which competes with the Go-execution process. Since the starting point of the Go-execution process is biased toward one of the response options, the Stop process has a greater speed. This period is completed by response execution or response inhibition.

Evidence from the literature suggests a relationship between SSD duration and response selection in the primary task, i.e., the duration of the Go-selection process. Therefore, HRM needs clarification or even modification (Bissett et al., 2021). We believe that this clarification should be made in terms of the structure of the model itself, considering the selection and response implementation stages of

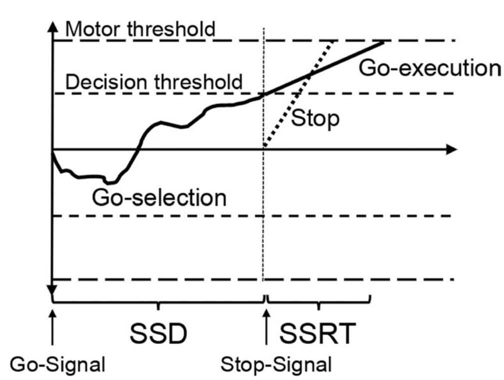

Fig. 1 Two-stage model of the Stop-Signal Task

the Go process. To test this hypothesis, we designed and conducted two experiments.

Experiment 1 was aimed at identifying the processes taking place during the SSD period by constructing a modified SST with the additional stimulus category Cued-Go. These trials have two periods: (1) preparatory response period between a cue and an imperative Go signal, and (2) motor period between an imperative signal and a motor response. During the preparatory period, also called the "foreperiod" (FP), a decision or response selection takes place (Maslovat et al., 2019; Shin & Proctor, 2018). A long foreperiod leads to the emergence of a complex effect including both a decrease in sensory thresholds for response-relevant features of the imperative signal (Job et al., 2019; Thomaschke et al., 2011b) and a chronometric reduction of the associated higher-accuracy CRT (Maslovat et al., 2019; Shin & Proctor, 2018; Thomaschke et al., 2011a, 2011b). Korolczuk et al. (2018) investigated the mechanisms of response preparation and found an increase in general response inhibition and selected response facilitation. Thus, during the preparation period the motor program conflict is resolved, and the response is therefore executed as a simple process similar to a prepared reflex (Hommel, 2000).

The duration of FP in Cued-Go trials in Experiment 1 is adaptively changed depending on the RT. Our previous study (Soghoyan et al., 2022) suggests that in the trials with more conflicting response selection, the adaptive FP is longer compared to less conflicting response selection trials. However, the RT did not statistically differ between conditions. Thus, the adaptive algorithm provides a measurement of the duration of response selection process, regardless of the duration of the response execution.

If the SSD reflects the duration of the response selection, then we expect to found three distinct empirical results from Experiment 1: (1) A high proportion of commission errors for SS corresponding to the correct Go response, indicating the completion of the response selection process; (2) the durations of SSD and adaptive FP will not differ statistically; and (3) SSD and adaptive FP will have a significant positive correlation. If these hypotheses are confirmed, then we should conclude that adaptive FP and SSD reflect the same response selection process.

In Experiment 2 we move on from testing correlational and comparative relationships to manipulating of the stopping efficiency by varying response preparation period. In Experiment 2, participants performed a Cued-Go task, and a Stop-Signal was also presented in half of the trials after the enumerative stimulus. Constant FPs and constant SSDs had two duration levels: 200 and 500 ms (Bissett et al., 2021). If the SSD reflects the duration of the signal selection, then moving the selection stage of the Go process on the response preparation period should significantly complicate the task, since the execution of a more automatic process is more difficult to stop and therefore more commission errors should be expected. If the Go-selection and Stop processes are independent, then the number of errors associated with FP and SSD factors should be substantial, and the interaction between the factors should not be significant. On the other hand, if the Go-selection and Stop processes are interdependent during the response period, then a reliable interaction between the FP and SSD factors should be expected.

Experiment 1

Method

Participants

Thirty-six participants (mean age = 20.89 ± 0.31 years; education = 14.19 ± 0.15 years; six males) were recruited to take part in both experiments. All participants were Higher School of Economics university students with no history of neurological or psychological impairments. All participants volunteered to take part. Participants were recruited by advertisement, and they received a monetary reward for participating in the study.

Participants were included in the study if their duration of sleep on the eve of the session was more than 6 h, they had no alcohol intake for a minimum of 1 day, and no tonic drinks for more than 2 h before participation in the study. The study was approved by the Ethics Committee of the Higher School of Economics and conducted in accordance with the Declaration of Helsinki.

For Experiment 1 the data from eight participants were excluded for the analysis of Modified Stop-Signal Task: four due to longer error RTs than Go-RTs and four due to low error rates (< 34%) for the stop responses. The final number of participants was 28 (age = 20.93 ± 0.38 years; five males; education = 14.14 ± 0.18 years).

To determine the detectable effect size, a sensitivity analysis was conducted using G*Power 3.1 (Faul et al. 2007). For Student's t-test a large effect size (0.8) with a power of 95% can be achieved with a total sample size of 23 subjects. For correlation a large effect size (0.8) with power of 95% can be achieved with the total sample size of ten subjects.

Procedure

All participants completed the tasks individually in a room with controlled lighting, sitting in a chair at a desk. The computer monitor was positioned perpendicular to the gaze at approximately 60-cm viewing distance. The participants first filled out a demographic questionnaire, and then they completed the experimental tasks. Finally, they were debriefed at the end of the session.

Instructions

The vignette with the experimental instructions for the main task was presented in the center of the screen prior to the main task. Participants were instructed to produce their responses as fast and as accurately as possible. If the participant had further clarification questions, these were answered by the experimenter verbally. The time of familiarization with the instructions was controlled by the participants.

Stimuli

The stimuli were presented on a computer screen centrally against a gray background. There were three categories: Cues, Imperative Go, and Stop-Signals. A square and a cross were used as Cues, presented with a rotation angle of 0° or 45°. The Cues were white, 2.8 cm wide, and had an angular size of 2°40' with a viewing distance of 60 cm. The Imperative Go signal was a green circle and the Stop-Signal was a red circle, both 5.5 cm in diameter and with an angular size of 5°15' with a viewing distance of 60 cm.

The subjects were required to press the left arrow on the keyboard when presented with a square and the right arrow on the keyboard when presented with a cross.

SST was programmed in accordance with the guide (Verbruggen et al., 2019) with an additional category of stimuli, referred as "Cued-Go." Stop-Signal trials consisted of the presentation of a Stop-Signal at variable delays following the presentation of the Go-Signal. The period between Go and Stop signals was designated as the Stop-Signal Delay (SSD) and changed according to the adaptive tracking procedure. Upon successful inhibition of the response by the participant, the SSD was increased by 50 ms at the next presentation of the SS; if participant made a response, then the SSD was decreased by 50 ms at the next presentation of the SS. The starting value of the SSD was 500 ms (Fig. 2A).

For the Cued-Go stimuli with the adaptive foreperiods (FP_{ad}), the length was updated based on the RT (RT_{ad}) in the previous trial from this category in accordance with the following formula:

$$FP_{n+1} = FP_n + 0.5 \times (RT_n - RT_h) \quad (1)$$

where FP_{n+1} is the foreperiod duration in n+1 trial, RT_n is the RT in trial n, and RT_h is the RT history. The coefficient 0.5 was used to maintain a balance between large and small changes in the foreperiod lengths, keeping a balance between liberal and conservative changes.

The initial value for the adaptive FP was 500 ms.

Following the calculation of the foreperiod length, the RT history parameter was updated according to the following formula:

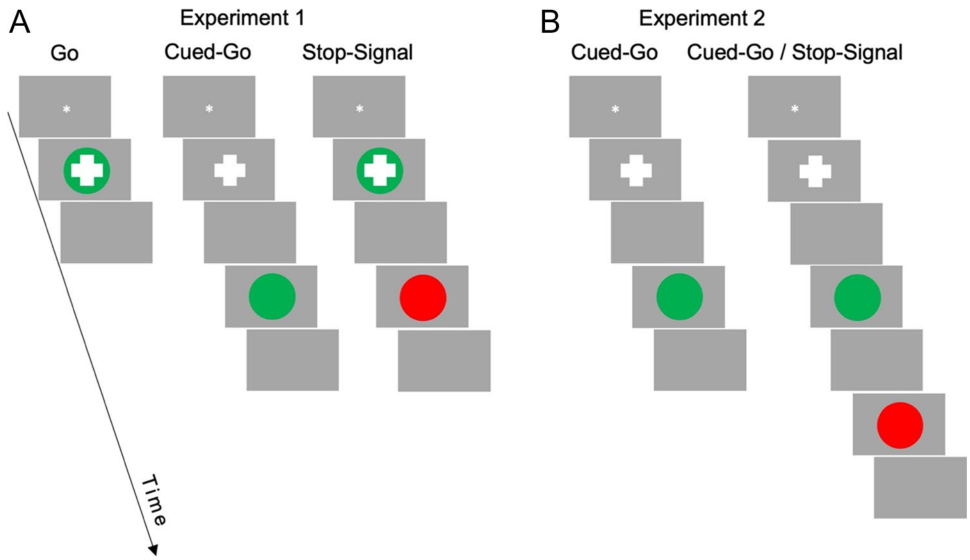

Fig. 2 Trial structure for Experiment 1 (**A**) and Experiment 2 (**B**)

$$RT_{h+1} = RT_h + 0.3 \times \left(RT_n - RT_h\right) \quad (2)$$

where RT_h is a weighted moving average of the response latency history and the RT_n is the reaction time in the trial n.

The logic of these calculations is as follows. As a result of calculating formula (2), we obtained smoothed RTs. This indicates the central tendency of the reaction's latency, which changed after each trial. Then using formula (1), we calculated the weighted difference between RT_n and smoothed RT_h. This difference is then added to the FP_n value and composed as the FP_{n+1} value. Thus, the excess of latency in trial *n* in relation to the individual response latency (smoothed RT_h) leads to an increase in FP_{n+1} in the next trial, which in turn should lead to a decrease in RT. Our previous study (Soghoyan et al., 2022) showed an increase in the duration of adaptive FP with an increase in the complexity of response selection with non-significant differences in the duration of the response-time period.

For the Go trials an asterisk was first presented for 800 ms, then the Cue and Imperative Go signal for 200 ms were presented simultaneously – Cue over the Go signal. For the Cued-Go trials an asterisk was first presented for 800 ms, then a Cue for 200 ms, followed by a foreperiod of varying duration and Imperative Go stimulus for 200 ms. For the SS the trial structure was the same as for Go trials, except the SS signal, presented for 200 ms after a variable SSD. The waiting time for a response was 1,400 ms. The intertrial interval was randomized from 1 to 2 s.

Training

Before completing the main block, participants performed a training session consisting of 48 trials. This practice session differed from the main experimental session in terms of the presence of a cue regarding the correspondence rule between stimuli and responses presented at the bottom of the screen and feedback for 500 ms signaling the correctness or an absence of a response after each trial. Following the training block, participants received feedback about the total accuracy of their responses. If the number of correct responses was above 80% for Go and Cued-Go trials and from 40–60% for Stop-Signal trials, then the participant automatically proceeded to the main task. Otherwise, the training block was repeated. The experimenter advised performing the responses faster or slower depending on the initial result. Participants performed no more than two training blocks.

Main task

Experimental trials were presented in individually randomized sequences divided into four blocks, separated by the pause periods. A total of 320 stimuli were presented: 160 Go trials, 80 Cued-Go trials, and 80 Stop-Signal trials.

Data processing

The RT data were preprocessed separately for each category. Data preprocessing included the following steps. First, the number of trials with no response was calculated. Second, all trials with premature responses were removed. A response was considered premature if it occurred before the Imperative Go signal onset. Third, trials with extremely early/anticipatory responses, RT < 100 ms, were removed. Fourth, trials with outlier responses over 2.5 SDs from the sample mean were removed.

To calculate the SSRT, commission errors and premature responses were included in the analysis (Verbruggen et al., 2019). SSRT was calculated using the mean method as the difference between mean Go-RT and mean SSD. In the Stop-Signal task, we also calculated the percentage of trials in which commission errors matched the Go signal Cue. That is, if the Go signal indicated a left arrow on the keyboard and commission error was a left arrow, then commission error corresponded to the correct Go response. Otherwise, if the required reaction in the primary task and the commission error did not match, the reaction was inaccurate. In the case of completion of the reaction selection period in the primary task, the percentage of commission errors corresponding to the correct Go-signal reaction will be close to 100%.

Data analysis

Mean FP_{ad} values for Cued-Go trials and mean SSD values for SS trials were subjected to a Student's t-test, as were mean RT_{ad} values for Cued-Go trials and mean Error RT values for SS trials. The percentage of commission errors corresponded to the accurate Go reaction for Stop-Signal trials and the percentage of positive responses in Cued-Go trials was also subjected to a Student's t-test.

The relationship between the variables was assessed by the Pearson correlation coefficient. The significance level was set at 0.05.

The experiment was designed and implemented using PsychoPy3 (release 2020.2.10) software (Peirce et al., 2019).

Results

The first stage of the analysis was aimed at establishing the independence between Go and Stop processes for the Stop-Signal trials. We registered shorter Commission Errors RTs compared to Go-RTs (mean (M) ± standard error (SE), Error RT = 681 ± 29 ms; Go-RT = 804 ± 36 ms; $t(27) = 11.35$, $p < 0.001$, 95% confidence interval (CI) = [30–217], Cohen's $d = 0.70$) (Fig. 3A). Go-RT and SSRT values showed a low correlation (Table 1). Error rate was 47.86 ± 0.74%. Thus,

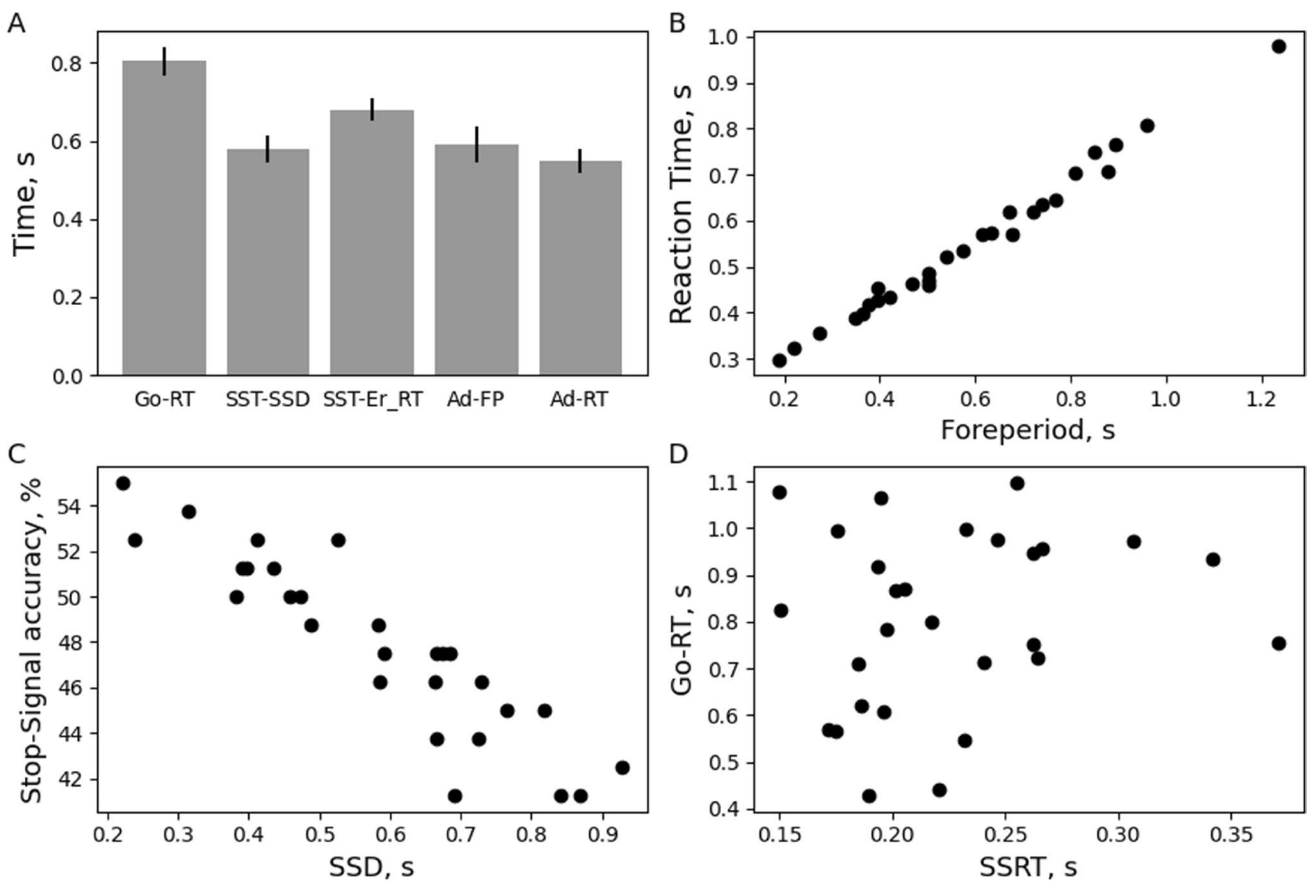

Fig. 3 Results of Experiment 1. (**A**) Mean and SE for Go-RT, SSD, Commission errors RT, adaptive FP and RT. (**B**) Scatterplot of correlation between adaptive FP and adaptive RT for Cued Go trials. (**C**) Scatterplot of correlation between SSD and accuracy for Stop-Signal trials. (**D**) Scatterplot of correlation between SSD and Go-RT

Table 1 Correlation matrix of Go-RT, SS and Cued Go

	Go-RT	SS CE RT	SSD	SSRT	FP_{ad}	RT_{ad}
Go-RT		0.97*	0.96*	0.18	0.83*	0.84*
SS CE RT			0.96*	0.08	0.81*	0.81*
SSD				-0.10	0.80*	0.81*
SSRT					0.12	0.13
FP_{ad}						0.99*
Mean	804	681	579	225	549	590
SD	192	156	190	54	160	246
95% CI	731–877	622–740	507–651	205–245	489–609	497–683

*p < 0.05

SS CE RT Stop-Signal Commission Errors reaction time

the basic conditions for the independence of Go and Stop processes for SST were met.

Our first assumption was that the number of commission errors matching the accurate Go response would be relatively high. We calculated the percent of these Commission Errors for SS and found that it was 97.25 ± 0.66%. Compared with a random response (50%), this result revealed a high significance (t(27) = 71.67, p < 0.001). Thus, the Go process in the SSRT period is simple and the selection of the response occurred in the SSD period.

According to our second assumption, the response selection is completed before the Stop-Signal presentation. As a result, SSD for SS trials should not differ from the adaptive FP duration for the Cued-Go trials. We found that the mean duration of the SSD for the Stop-Signal trials did not differ statistically from the mean duration of the adaptive FP for the Cued-Go trials (SSD = 579 ± 36 ms; Cued-Go FP = 590 ± 46 ms; t(27) = 0.41, p = 0.685, 95% CI = [-129–107], Cohen's d = 0.05).

Additionally, we calculated the difference between the SSD duration for Stop-Signal Commission Errors and the adaptive FP duration for the Cued-Go stimulus. In both cases, a response was made. Insignificant differences was also found (SSD for Commission Errors = 606±36; Cued-Go FP = 590 ± 46; t(27) = 0.58, p = 0.564, 95% CI = [-103, 134], Cohen's d = 0.07).

Thus, SSD and adaptive FP did not differ from each other. Perhaps they reflect the same process. Additional information may provide the correlation analysis.

At the same time, Commission Error RTs for SS trials were longer compared to adaptive RTs for Cued-Go trials (SST Commission Error RT = 681 ± 29 ms; Cued-Go-RT = 549 ± 30; t(27) = 7.07, p < 0.001, 95% CI = [46–216], Cohen's d = 0.84) (Fig. 3A).

Also, percent of Commission Errors matching correct Go signal for SS trials was higher than the percent of correct responses for the Cued-Go trials (SST: percent of Commission Errors matching Go signal = 97.25 ± 0.66%; Cued Go: percent of correct response for the Cued-Go trials = 87.90 ± 1.07%; t(27) = 7.80, p < 0.001, 95% CI = [6.83–11.87], Cohen's d = 1.99).

Thus, subjects were more cautious in their responses for SS compared to Cued-Go trials.

Finally, we hypothesized that if the mean SSD duration for the Stop-Signal and the mean duration of the adaptive FP for the Cued-Go stimulus reflect the duration of the same response selection process, then there should be a significant correlation between these variables. This correlation was indeed reliable (Table 1).

Additionally, we found a significant positive correlation between Go-RT and adaptive RT, as well as an insignificant correlation between SSRT and adaptive RT.

Thus, the assumption regarding the completion of the response selection process at the end of the SSD was confirmed by the analysis of the Commission Errors for SS trials, unreliable differences in duration and a high reliable correlation between SSD independent variable, reflecting the duration of the response selection process, adaptive FP.

Discussion

According to the Sequential Stage Model (Sternberg, 2001), there are three stages between stimulus presentation and response registration: (1) sensory processing of the stimulus, (2) decision-making, and (3) motor response execution. Since these stages are independent of each other (Haith et al., 2016), we can transfer the decision-making process to the period between the cue presentation and the imperative signal. Thus, two periods are created: (1) a foreperiod between the cue and the imperative stimulus presentation, and (2) a reaction period between the imperative stimulus presentation and the key response. FP duration and RTs have been shown to be negatively correlated (Maslovat et al., 2019; Shin & Proctor, 2018; Soghoyan et al. 2022; Thomaschke et al., 2011a, 2011b). The adaptive algorithm for determining individual FP duration used this dependence as a forward model. The algorithm works as an inverse solution to estimate the duration of latent variable FP from the registered RT values. Thus, the goal of the adaptive algorithm is to relocate preparatory processes that are not rigidly related to reaction execution beyond the reaction period and to estimate the individual foreperiod duration. In essence, it is a gradient descent to the minimum values of the imperative stimulus waiting period with the maximum duration of the foreperiod. So, the duration of the FP may vary depending on the task and the participants regardless of the reaction execution period duration. As demonstrated in our previous work (Soghoyan et al., 2022), an increase in the response selection difficulty leads to increasing the FP duration, but not the reaction period.

In Experiment 1, we compared the results of Cued-Go Task with the well-known and widely used Stop-Signal Task (Logan & Cowan, 1984). Both tasks produce separate periods of response preparation and execution based on adaptive algorithms but are aimed at different effects – response execution and response inhibition. There were three main findings in Experiment 1.

First, the number of Commission Errors matching the accurate Go response for the SS trials was close to 100%, indicating simple reactions at least for fast responses. Since the primary task was choice RT, which included the stages of response selection and implementing a simple reaction, the localization of a simple Go-execution process within the SSRT period indicates, firstly, that the competition between the Go and Stop processes occurs during the SSRT period. Logan and Cowan (1984) repeatedly note that the Stop process is simple. A high percentage of Commission Errors toward a correct Go response indicate that the competition with the Stop process is also a simple Go-execution process. Secondly, the Go-selection sub process must be completed by this time and therefore it must be localized in the SSD period. Thus, the adaptive algorithm in SST is based on the final result of the implementation or absence of response localized SSD at the boundary of the selection and response stages, since the stages are independent of each other. Adaptive tuning based on success of response inhibition affects the reaction execution time but cannot affect the response selection.

Second, the duration of the response selection in terms of the adaptive FP values for Cued-Go trials and the duration of SSD for SS trials did not differ statistically. This result cannot be considered on its own, since the lack of differences per se can be due to a variety of reasons. Only in the presence of a high significant correlation we can assume the existence of a common process of selection of the response for two types of trials. However, we found longer Commission Error RTs for SS trials compared to adaptive RTs for Cued-Go trials, indicating a more cautious response strategy for SST compared to Cued-Go. This assumption is also confirmed by the accuracy data analysis. Theproportion of Commission Errors matching the accurate Go responses for SS trials was greater than the proportion of correct responses for Cued-Go trials, also reflecting a more rigorous response selection process for SST compared to the Cued-Go task. Such fast and less accurate responses for Cued-Go may be due to the long FP. FP duration depends on several time-consuming processes including sensory analysis and response selection. Additionally, trial structure breaks the flow of the processes into periods, and if the processes are executed in parallel, their separation increases the FP duration as well as the RT. Also, additional imperative Go signal inclusion distracts participants' attention and requires sensory analysis of the stimulus, which is also time consuming. Nevertheless, Logan and Cowan (1984) argue that presenting a Stop-Signal does not interfere with the Go process. Starting points for response execution are therefore moved closer to response threshold with responses becoming faster and less accurate.

Third, the duration of adaptive FP and SSD were found to be strongly correlated. This relation allows identification of the processes, which take place in SSD and which are implicit in the Go-RT. The correlation between Go-RT and SSD does not clarify the processes they comprise – in Go-RT they proceed in an implicit way, and no cognitive process hypotheses have been proposed for SSD. Our previous study (Soghoyan et al., 2022) showed that in an adaptive algorithm for Cued-Go trials, FP values are associated with the duration of the response selection process, regardless of the duration of the selected simple response period. Together with the high positive correlation between FP and SSD obtained in the present study, we hypothesize that they share the common process of the response selection.

Additionally, the correlation between Go-RT and adaptive FP is somewhat lower compared to the correlation between Go-RT and SSD. Perhaps this is due to differences in the overall trial structure for SST and adaptive FP. By position HRM Stop process and Go process are independent of each other, and SSD in the SST structure is part of the Go process. Also, Commission Errors are also part of the Go process, which won the competition with the Stop process. This is evidenced by the high positive correlation between Go-RT and Error RT. Thus, Go-RT, Error RT and SSD have high positive correlations due to belonging to the same Go process.

Similarly, adaptive FP and adaptive RT are highly correlated due to belonging to the Cued-Go process. However, correlations between these two groups of variables were lower, possibly due to the difference in the trial structure. In adaptive FP trials the subject is explicitly instructed to first prepare the reaction and then perform it. Thus, the execution of the reaction is predicted, and the process uncertainty was low. In SS trials, participants cannot predict SS presentation in a given trial, so process uncertainty was higher. Difference in uncertainty is confirmed by RT and accuracy data described earlier. Thus, despite the unreliable statistically differences in the response preparation periods (FP for Cued-Go trials and SSD for SS trials), we propose that the participants used divergent strategies – conservative for SST with greater proactive response control and more liberal for Cued-Go with faster and less accurate responses.

Based on these three findings, we conclude that SSD incorporates the processes of response selection and inhibition of an alternative one in the primary choice RT task, and, consequently, the processes of voluntary inhibition of the target response in the SS task occur during the response execution period.

Experiment 2

Method

From comparative and correlative analysis, we moved on to manipulation. We assumed that if the Stop process depends on the level of preparation of the Go process (Chikazoe, et al., 2009; Ficarella & Battelli, 2019; Li et al. 2005; Wang et al., 2018), then a longer FP for the Go signal should significantly reduce the response stopping success. Also, Bissett et al. (2021) found that during SSD periods of 200–500 ms the Stop and Go processes are independent. Thus, in this study, Cued-Go trials were presented and in half of the trials SS were presented additionally. We built a factorial design where FP and SSD were 200 and 500 ms. Thus, there were six categories of trials: FP_{200}, FP_{500}, FP_{200}/SSD_{200}, FP_{200}/SSD_{500}, FP_{500}/SSD_{200}, FP_{500}/SSD_{500}.

Participants

The data from three participants were excluded from the analysis due to high error rates. The final number of participants was 33 participants (age = 20.88 ± 0.32 years; five males; education = 14.18 ± 0.13 years).

For repeated-measures analysis of variance (ANOVA) with a 2 × 2 design a large effect size (0.8) with power of 95% can be achieved with the total sample size of N = 14 subjects.

Stimuli

The stimuli were presented on a computer screen centrally against a gray background. There were three categories: Cues, Imperative Go, and Stop-Signals. A square presented with a rotation angle of 0° or 45° was used as the Cue. The Cues were white, 2.5 cm wide, and had an angular size of 2°23’ with a viewing distance of 60 cm. The Imperative Go signal was a green circle and Stop-Signal was a red circle, 3.7 cm in diameter and having an angular size of 3°32’ with a viewing distance of 60 cm.

During the experimental trial, an asterisk was first presented for 800–1,200 ms, then a Cue for 100 ms. This was followed by a foreperiod of 200- or 500-ms duration, followed by an Imperative Go stimulus for 100 ms. Upon presentation of the Imperative Go signal, the participants performed a motor response by pressing the left or right arrow on the keyboard. The presentation of the square was associated with pressing the left arrow on the keyboard, the presentation of the rhombus (a 45° rotated square) was associated with pressing the right arrow on the keyboard. In a half of the trials following Imperative Go signal were presented the Stop-Signal for 100 ms with constant SSD equaling 200 or 500 ms. The waiting time for a response was 1.5 s. The intertrial interval was randomized from 1 to 2 s (Fig. 2B).

Training Before completing the main block, the participants performed two training sessions. The first training session consisted of Cues and Imperative Go stimuli with FP 200 and 500 ms. Participants were required to respond to the imperative Go signal as fast and accurately as possible. After each trial, participants received feedback over 600 ms. There were four feedback types: correct response, incorrect response, response absent, and slow response (RT > 800 ms). The first training session included 32 trials.

The second training session included additional Stop-Signals in half of the trials. The feedback was the same as in previous training session. The second training session included 48 trials.

The experimental session included 384 stimuli, 96 trials for FP_{200} and FP_{500} as well as 48 trials for each subcategory of FP/SSD. The stimuli were presented in individually randomized sequences in three blocks.

Data processing

RT data were preprocessed separately for each category. Data preprocessing included the following steps. All trials with premature responses were removed. A response was considered premature if it occurred before the Go signal onset. Trials with no response, extremely early/anticipatory responses (RT < 100 ms), and outlier responses over 2.5 SDs from the sample mean were removed. The number of error responses was calculated for subsequent analysis.

Data analysis

Error rates for FP_{200} and FP_{500} trials were subjected to Student’s t-test analysis. Error rates for FP_{200}/SSD_{200}, $FP_{200}/$

SSD_{500}, FP_{500}/SSD_{200}, FP_{500}/SSD_{500} trials were subjected to multivariate ANOVA with FP (FP_{200}, FP_{500}) and SSD (SSD_{200}, SSD_{500}) factors. Sphericity was corrected using the Greenhouse-Geisser criterion, the effect sizes were estimated by the partial eta squared. Multiple comparisons were made with Bonferroni-corrected p-values. The significance level was set at 0.05. The experiment was designed and implemented using PsychoPy3 (release 2020.2.10) software (Peirce et al., 2019).

Results

The effectiveness of FP duration manipulation was tested using the RT and Error Rate data. The RT for FP_{200} was longer compared to FP_{500} (FP_{200}: RT = 740 ± 19 ms; FP_{500}: RT = 711 ± 22 ms; t(32) = 3.26, p = 0.003, Cohen's d = 0.25) (Fig. 4A). For FP_{200}, the Error Rate was higher compared to FP_{500} (FP_{200}: Error Rate = 6.76 ± 0.76%; FP_{500}: Error Rate = 4.17 ± 0.84%; t(32) = 3.33, p = 0.002, Cohen's d = 0.56) (Fig. 4B). Thus, an increase in the duration of the preparatory period decreased the response time and increased the accuracy of the responses, so, during FP_{500} response preparation was more completed than during FP_{200}.

The main question in Experiment 2 was how the response inhibition success would vary with different degrees of Go response readiness. In half of the trials, after presentation of the imperative Go signal, Stop-Signal were presented with SSD of 200 or 500 ms, and the number of Commission Errors was calculated. A multivariate ANOVA with FP (200 vs. 500 ms) and SSD (200 vs. 500 ms) factors revealed significant main effects of FP (F(1,32) = 5.06, p = 0.032, ε = 1.000, $\eta_p^2 = 0.81$). The interaction between the factors was not reliable (FP × SSD: F(1,32) = 1.33, p = 0.258, $\eta_p^2 = 0.04$) (Fig. 4C).

With increasing FP duration, the number of Commission Errors increased from 25.05 ± 4.68% to 27.78 ± 4.83% and with an increase in SSD from 6.82 ± 1.84% to 45.01 ± 4.44%. Thus, the Go and Stop processes are independent, at least from 200 to 500 ms.

Discussion

Experiment 2 revealed that increasing duration of the preparatory period results in decreasing RTs and the increasing the Error Rates. So, our manipulation was successful; that is, the process of response preparation was at least partially moved to the post-cuing period. The main question in Experiment 2 was how the success of response inhibition changes with different FP durations. To this end, the Error Rates were calculated for each value of FP and SSD. As a result, we registered significant and independent effects of FP and SSD on the response inhibition success. An increase in SSD induced a substantial drop in the response accuracy. Also, a longer response preparation led to a decrease in the effectiveness of response inhibition.

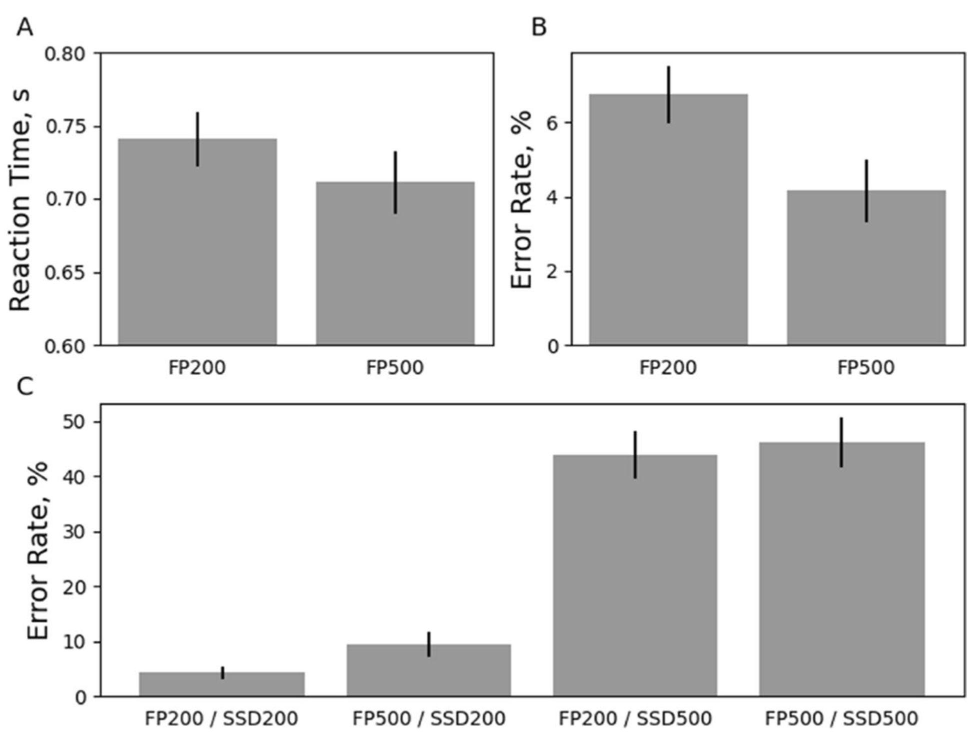

Fig. 4 Results of Experiment 2. (**A**) Reaction times for FP_{200} and FP_{500}. (**B**) Error rates for FP_{200} and FP_{500}. (**C**) Error rates for Stop-Signal trials

Since only a small part of the process has been transferred to FP (14%), we cannot conclude that this is the only process present within SSD. Perhaps the Go process includes both strategic and ballistic components. FP is associated with a strategic response preparation process (a pro-active top-down component) and it makes a small but independent contribution to the response inhibition efficiency (Chikazoe et al., 2009; Ficarella & Battelli, 2019; Li et al., 2005). The ballistic process is associated with programming and online control of the response execution and is the basis of the effect of SSD influence on the response inhibition effectiveness (a reactive component). As a result, the more controlled response selection processes are moved to the preparation period while motor programming and response implementation become less controlled (Maslovat et al., 2018; Maslovat et al., 2019).

Thus, an increase in the duration of FP caused an increase in the Error Rates regardless of the duration of the SSD, that is, at least part of the response selection process was transferred to FP. Together with the results of Experiment 1, this indicates that the SSD contains a response selection process independent from response inhibition process.

General discussion

Two experiments discussed in this paper investigated the nature of the processes that take place during the Stop-Signal Delay in the Stop-Signal Task. Experiment 1 demonstrated that the SSD in the SST structure incorporates the process of response selection. Experiment 2 showed that partial replacement of response selection process to the post-cuing period reduces reaction inhibition effectiveness independently of Stop-Signal Delay.

The stages of the Go process have been identified in several studies and integrated into a model of motor control (Sigman & Dehaene, 2005; Sternberg, 2001). However, these stages are not considered in HRM, making it difficult to investigate Go and Stop processes in detail. Some studies ignored this problem and did not report SSD values at all (Castro-Meneses & Sowman, 2018; Chao et al., 2009; van de Laar et al., 2014) or reported them as technical intermediate data used for calculating the target SSRT value (Boucher et al., 2007; Chikazoe et al., 2009). Meanwhile, the nature of the processes occurring following the presentation of the Go signal is important for the subsequent response control. We assumed that SSD in the SST structure includes processes associated with response selection in the primary task.

In Experiment 1 we compared the SSD with the variable associated with the response selection – duration of the adaptive FP (Soghoyan et al., 2022). Both indicators were calculated according to an adaptive procedure independently of each other based on different behavioral parameters – the success of response inhibition for calculating SSRT and the RT for calculating adaptive FP. According to the structure of the Stop-Signal Task, the SSD is part of the primary CRT Task, since SSD duration is calculated as the period before the Stop-Signal appears. Based on these data, and the staged structure of the Go process (Sigman & Dehaene, 2005; Sternberg, 2001), we assumed that SSD duration corresponds to the sensory analysis and response selection phases for the CRT. Our previous study (Soghoyan et al., 2022) shows that the adaptive FP also reflect the individual duration of the response selection process. Since these two variables are related to the duration of the same selection process, they must also be related to each other.

In support of this hypothesis, the results of Experiment 1 showed that SSD and adaptive FP show similar durations and high correlation. This hypothesis is also supported by the data on a high percentage of Commission Errors following presentation of Stop-Signal corresponded to the accurate Go response. Thus, we concluded that response selection took place during the SSD period. These results are in line with the data showing that the complexity of response selection (Logan et al., 1984; Logan et al., 2014) and perceptual decision-making (Middlebrooks & Schall, 2014) impact the only SSD, but not the SSRT. Otherwise, factors that affected SSRT, such as modality and intensity of the Stop-Signal, are not accompanied by the SSD changes (Carrillo-de-la-Peña et al., 2019; Morein-Zamir & Kingstone, 2006). Thus, Stop-Signal Task is composed of two successive and independent stages, similar to the CRT task, of response selection period and response execution/inhibition period.

However, findings from Experiment 1 are comparative and leave open the question of whether we can manipulate the response selection independently from a controlled inhibition of the target response. To investigate this, we conducted Experiment 2 where we moved the selection process to the post-cuing period and analyzed the effect of this replacement on the response inhibition success. Results of Experiment 2 show that the response selection occurred independently of the response inhibition. A large proportion (effect size equal 81%) of response inhibition is explained by the SSD. High efficiency of response inhibition ($6.82 \pm 1.84\%$ of Commission Errors) is found with a short SSD (200 ms); however, a longer SSD (500 ms) leads to more errors ($45.01 \pm 4.44\%$ of Commission Errors). The results for SSD_{500} are consistent with those of Experiment 1, which showed a slightly higher mean SSD (579 ± 36 ms) and a slightly higher percentage of inhibited responses ($47.86 \pm 0.74\%$). Since all subjects took both tests, we calculated the correlation between the percentage of inhibited responses in Experiment 1 and the average percentage of inhibited responses between the FP_{200} and FP_{500} conditions for SSD_{500} in Experiment 2. We found a significant relationship (Pearson rho = 0.45, p = 0.023) between these two variables without considering the fact that the SSD_{500} for the subjects was presented at different phases of the reaction. Thus, we believe that the results of the experiments complement each other and expand the evidentiary basis of our hypothesis.

The response inhibition depends on the readiness of the Go process with much smaller effect size (14%). For a short post-cuing period (200 ms), the selection process is only partially transferred, and it continues during the SSD period, leaving room for the more effective control of response inhibition (25.05 ± 4.68% of Commission Errors). For a long post-cuing period (500 ms), a smaller fraction of the selection process remains within the SSD period, negatively affecting the probability of response inhibition (27.78 ± 4.83% of Commission Errors).

Thus, findings from Experiment 2 additionally confirm the different natures of processes ongoing within the SSD and SSRT periods. The response selection process, however, is only partially transferred to the preparatory period – perhaps due to the proactive control of the reaction. Numerous studies have shown the role of proactive control in the implementation of the reaction. Specifically, a decrease in the frequency of presentation of a Stop-Signal increases the Go-RT (Lee & Kang, 2020; Verbruggen & Logan, 2009). In Experiment 1 of the present study, the Stop-Signal was presented only in a quarter of the trials, and therefore the role of the proactive deceleration of Go-RT was strongly pronounced. However, in Experiment 2 the situation looks more complicated. If the response selection process is supposedly partially transferred to the post-cuing period, then what happens to the proactive delay in the response? Perhaps the proactive expectation of the inhibition stimulus did not become transferred to the post-cuing period and remains in the post-Go signal period, since the Cue was presented in all trials, while the Stop-Signals were presented only in half of the trials. Therefore, proactively waiting for a Stop-Signal should create a Go-RT prolongation effect and be reflected in a decrease in efficiency of response inhibition.

Our study also has certain limitations.

First, the Cued-Go algorithm needs further development with the involvement of the mathematical theory of optimal control for a more efficient and stable identification of the individual duration of the preparatory period. Second, the differences between the structures for Go and Cued-Go trials may result in differences in the response strategy. For Go trials, the situation is uncertain since the participant does not know whether SS will be presented in the current trial. For Cued-Go, the presentation of cue makes the situation certain, since it is followed by Go and SS will not be presented. Based on the accuracy and the speed of responses, the dynamics of cognitive and motor processes may differ. For more accurate and valid conclusions, it is important to make these conditions more similar in future research. Third, two levels of FP and SSD were used in Experiment 2, leaving only an assumption about inhibition function for different levels of FP duration. Fourth, a part of the response selection process in Experiment 2 is removed from the SSD, since the RT decrease only 29 ms, which is about 4% of the Go-RT. Perhaps a weak effect of FP is responsible for a relatively low response inhibition efficiency and the presence of an unreliable interaction between FP and SSD. An increase in the proportion of the response selection process that is transferred to the post-cuing period can reveal this interaction. Fifth, the results of Experiment 2 do not allow us to draw a conclusion about the change in the speed of the inhibition process, since there were not enough data to calculate RT. In the future experiments increase the number of trials allow to obtain RT data. Sixth, the algorithm is tested using only one task type, namely, response selection from several alternatives. Naturally, this needs to be generalized to other tasks, for example, economic and sensory decision-making tasks. Also, a sensory decision-making task (e.g., the Random Dot Motion Task) could offer an opportunity to calculate DDM parameters, such as boundary separation and drift rate. Finally, our results need to be extended to include experiments using participants with impaired motor control. Since the algorithm calculates FP based on RT, impaired motor functions may result in an inability to allocate sustained FP values.

To conclude, the results of Experiment 1 confirmed our hypothesis that SSD reflects the duration of the response selection process. Experiment 2 showed that this process has an independent effect on the effectiveness of voluntary inhibition of the target response. Based on the results, we propose a two-stage model of response inhibition in SST – the first stage is response selection in primary CRT and the second stage is response inhibition follow the SS presentation. Despite our findings, the proposed hypothesis requires confirmation in follow-up studies.

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Data availability Data for the experiments reported here are available via the Open Science Framework at https://osf.io/whqgy/, and none of the experiments was preregistered.

Declarations

Conflicts of interests The authors have no relevant financial or non-financial interests to disclose.

Ethics approval Approval was obtained from the ethics committee of the Higher School of Economics. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to participate Informed consent was obtained from participants included in the study.

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